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From Science to Policy 12

Closer-to-Nature Forest Management

Jørgen Bo Larsen, Per Angelstam, Jürgen Bauhus, João Fidalgo Carvalho, Jurij Diaci, Dorota Dobrowolska, Anna Gazda, Lena Gustafsson, Frank Krumm, Thomas Knoke, Agata Konczal, Timo Kuuluvainen, Bill Mason, Renzo Motta, Elisabeth Pötzelsberger, Andreas Rigling, Andreas Schuck

Authors

Jørgen Bo Larsen, University of Copenhagen, Department of Geosciences and Natural Resource Management, Denmark

Per Angelstam, Inland Norway University of Applied Sciences, and Swedish University of Agricultural Sciences, Sweden

Jürgen Bauhus, University of Freiburg, Institute of Forest Sciences, Germany

João Fidalgo Carvalho, University of Tras os Montes Alto Douro, CITAB, Dep Forest Science and Landscape Architecture, Portugal

Jurij Diaci, University of Ljubljana, Biotechnical Faculty, Department of Forestry, Slovenia

Dorota Dobrowolska, Forest Research Institute, Poland

Anna Gazda, Department of Forest Biodiversity, University of Agriculture in Krakow, Poland

Lena Gustafsson, Swedish University of Agricultural Sciences (SLU), Sweden

Frank Krumm, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Switzerland

Thomas Knoke, Technical University of Munich, Germany

Agata Konczal, European Forest Institute

Timo Kuuluvainen, Department of Forest Sciences, University of Helsinki, Finland

Bill Mason, Forest Research, Northern Research Station, Roslin, Scotland, UK

Renzo Motta, University of Turin and Italian Society of Silviculture and Forest Ecology, Italy

Elisabeth Pötzelsberger, European Forest Institute

Andreas Rigling, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, and Swiss Federal Institute of Technology ETH, Switzerland

Andreas Schuck, European Forest Institute

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Executive summary

What is Closer to Nature Forest Management?

Closer-to-Nature Forest Management is a *new* concept proposed in the EU Forest Strategy for 2030, which aims to improve the conservation values and climate resilience of multifunctional, managed forests in Europe. Building on the latest scientific evidence, this report attempts to **define the concept** based on a set of **seven guiding principles**. It also outlines a **framework/checklist for flexible European-wide implementation of the concept**.

The 7 principles of Closer-to-Nature Forest Management are:

1. Retention of habitat trees, special habitats, and dead wood
2. Promoting native tree species as well as site adapted non-native species
3. Promoting natural tree regeneration
4. Partial harvests and promotion of stand structural heterogeneity
5. Promoting tree species mixtures and genetic diversity
6. Avoidance of intensive management operations
7. Supporting landscape heterogeneity and functioning

This report analyses the current pressures on forest biodiversity as well as on the health of, and resilience in, managed forests. It examines existing nature-oriented forest management approaches in Europe and analyses their ability to support biodiversity, their stability and adaptability to uncertain future conditions. It proposes a definition, a set of guiding principles and a framework for flexible European-wide implementation of Closer-to-Nature Forest Management. Finally, it evaluates barriers and enablers for implementation and presents a list of existing networks that can be used to assist the dissemination of Closer-to-Nature Forest Management throughout Europe.

How can we implement this new concept?

1. Different regions need different management approaches: While the general principles of Closer-to-Nature Forest Management should be similar across all regions, varying but related management approaches should be used in different regions of Europe. This reflects the variation in forest types across the continent, differences in the intensity and scale of natural disturbance regimes, and the ways forests have been used in the past and will have to be managed in the future.

2. Learn from the past and consolidate existing networks and demonstrations: There is a long European tradition of nature-based forest management concepts, and there are many opportunities to learn from existing practices. Because the wider adoption of Closer-to-Nature Forest Management will require a substantial effort in knowledge transfer, it is very important to consolidate existing networks of trials and demonstrations. Such a knowledge transfer network should cover all major regions and forest types found in Europe and could be linked to others seeking to preserve traditional and sustainable management methods, cultural landscapes and their associated biocultural diversity. This will be invaluable in the ongoing social learning process and in helping to convince forest managers and other stakeholders of the benefits of this approach.

3. Use adaptive management as a way to tackle uncertainties: We need to regularly monitor forest responses to management interventions, evaluate these responses and adjust management strategies accordingly. A similar adaptive approach is urgently required to evaluate the impact of policy measures and support mechanisms proposed to encourage adoption of Closer-to-Nature Forest Management.

4. Not a quick-fix, long-term measures are needed: The introduction of Closer-to-Nature Forest Management is not a 'quick-fix' and policy makers must provide long-term and consistent support measures to encourage forest managers and other stakeholders to adopt this strategy. Support for forest owners for training and application of the strategy is key.

5. Review existing subsidy and taxation regimes for private owners: Convincing private owners to follow this approach will require the creation of schemes that reward them for providing ecosystem services. Closer-to-Nature Forest Management has the potential to support biodiversity, adapt forests to climate change and provide ecosystem services to a higher level than conventional forest management. There is an urgent need to review existing subsidy and taxation regimes affecting private forestry, and to consider how these might be changed to further the uptake of Closer-to-Nature Forest Management.

6. Develop and use new technologies and tools: There is a need to harmonize monitoring systems and to develop and use new technologies and tools (GIS, GPS and remote sensing) to ease management of these more diverse and structure-rich forests.

Finally, there are still some uncertainties about the effect of certain elements of Closer-to-Nature Forest Management on biodiversity conservation and ecosystem health, and how they will affect other ecosystem services including wood production under different management conditions throughout Europe. **This calls for more collective learning, experimentation and research.**

1. Introduction

Policy context and aim

Closer-to-Nature Forest Management is a concept proposed in the EU Forest Strategy for 2030 (EUFS 2021). The idea is to provide a vision of and direction for managed forests in Europe, which improves their conservation values as well as their climate resilience.

According to the EU Biodiversity Strategy 2030, biodiversity-friendly practices such as closer-to-nature-forestry should continue and be further developed. Correspondingly, the EUFS envisages that European forests will be healthy, diverse and resilient while contributing to enhancing biodiversity, maintaining rural livelihoods and supporting a diversified forestry sector based on Sustainable Forest Management (SFM). To that end, the EUFS seeks to build on the foundations of SFM with criteria, indicators and target thresholds that will help identify Closer-to-Nature Forest Management applications that will deliver improved ecosystem-based approaches to forest management. These will in turn enhance the long-term environmental and socio-economic viability of European forest landscapes.

The EUFS plans should lead to: 1) the development of a definition and adoption of guidelines for Closer-to-Nature Forest Management practices by the second quarter of 2022, and 2) the development of a voluntary Closer-to-Nature Forest Management certification scheme by the first quarter of 2023.

Building on the latest scientific evidence, the aim of this report is:

- to analyse the current pressures on forest biodiversity as well as on health and resilience in managed forests
- to examine the range of existing nature-oriented forest management approaches and analyse their ability to support biodiversity, stability in and adaptability to uncertain future conditions
- to propose a definition, a set of guiding principles and a framework for flexible European-wide implementation of Closer-to-Nature Forest Management
- to evaluate barriers and enablers for the implementation of Closer-to-Nature Forest Management.

Background

Currently, there is a transition in many European regions towards a more multifunctional forest management approach. The overall objective is to deliver a wide range of ecosystem services to benefit present and future generations and societies, while enhancing biodiversity protection and reversing the degradation of ecosystems. Inevitably, seeking to provide this diversity of services can result in a decline in the supply of individual elements of the portfolio (van der Plas et al. 2016).

In general terms, natural forest ecosystems have been robust as a consequence of long-term adaptation to regional and local conditions. Their apparent resistance and resilience – i.e. their ability to withstand stress and recover from disturbances – is mainly based on structural, functional and genetic diversity.

However, a widespread focus on wood production in previous centuries has resulted in a simplification and homogenization of European forests in many regions, often exemplified by the creation of even-aged and single species stands. This has weakened the natural robustness of the forests, which is further challenged by global change (climate change, nutrient enrichment and introduction of new biotic stressors). These developments are already affecting forests in the form of increasingly severe disturbances (extreme heat and droughts, storms, fires, bark beetles, native and imported pests and pathogens), that compromise their capacity to sustain multiple ecosystem services.

Forests are also central to another global challenge – the loss of biological diversity. Forests are home to about 80% of land-based species worldwide, which highlights their central role as habitat (FAO, 2014). To give back space to nature, the EU Biodiversity Strategy for 2030 has proposed an overall target to protect at least 30% of the EU land area under an effective management regime, of which one-third (i.e. 10% of the EU land area) should be put under strict legal protection. This is consistent with the 'third of third' principle in

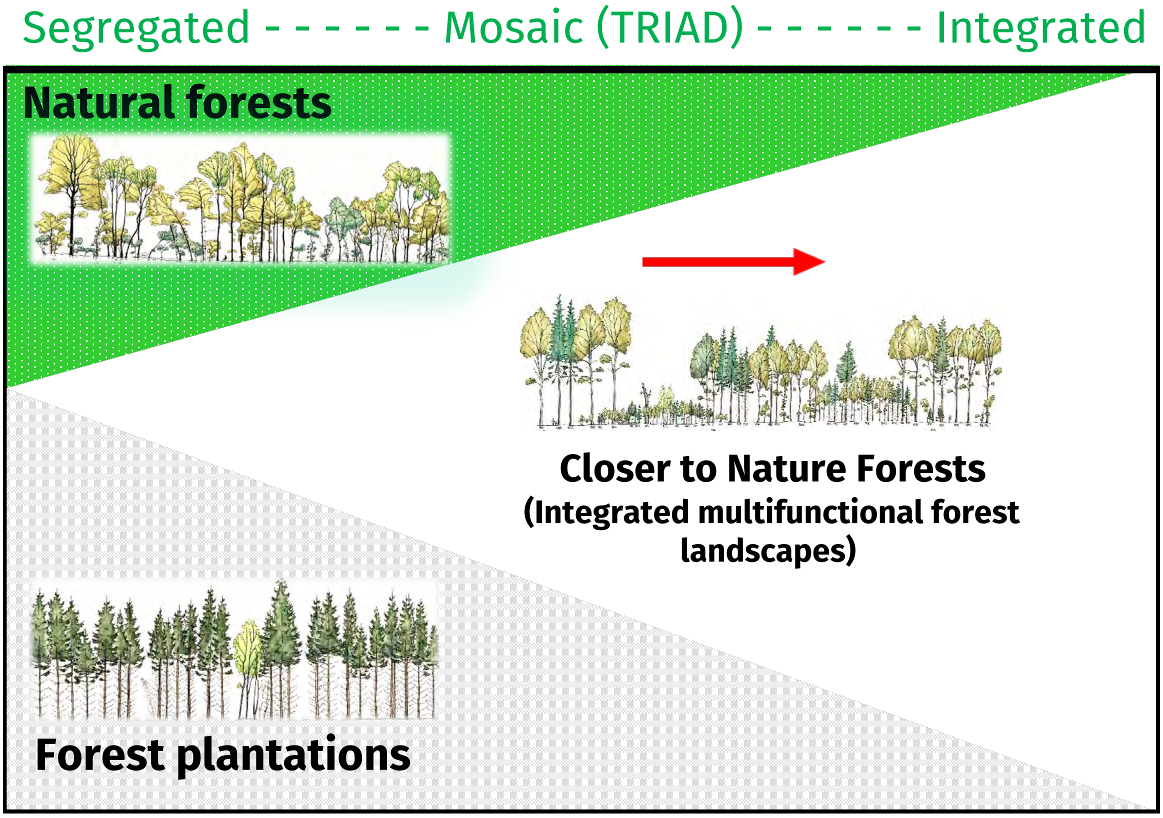

Figure 1: Landscape segregation and integration - a continuum (modified after Larsen, 2009). The term 'triad' in forestry refers to a landscape management regime composed of three parts: (1) intensive plantation management, (2) ecological forest reserves, and (3) a matrix of forests managed for multiple uses following the principles of ecological forestry. Note that the figure only shows the principles of complementarity between segregative and integrative management. The profile diagrams of the forest types shown relate to central European conditions, a different representation would be needed for other biomes.

conservation science (Hanski 2011). Forest ecosystems will need to contribute to this goal. Besides their contribution to the strict protection target, the integration of conservation measures into the management of multifunctional (production) forests is of crucial importance.

Efforts to conserve forest biodiversity rely on two overlapping approaches; 1) setting aside forests specifically for nature conservation in areas excluded from wood production (*functional segregation*) and 2) incorporating conservation measures within production-oriented forests (*functional integration*). These two approaches support each other: the more biodiversity is safeguarded through management while producing wood and other ecosystem services, the fewer areas must be set aside for pure biodiversity protection (Lindenmayer and Franklin 2002; Larsen 2009; Boncina 2011a; Bollmann and Braunisch 2013; Kraus and Krumm 2013).

Figure 1 shows the continuum of landscape segregation and integration. The situation to the left shows a completely segregated forest landscape with spatial separation of different forest management objectives: protection at the top, production at the bottom. Examples can be found in countries such as New Zealand with a shorter land use history than Europe where intensive forestry is located outside the big unmanaged forest reserves and there is nothing in-between. Moving right, an increasing proportion of the forested landscape is managed for multifunctionality, combining management for most objectives in the same forest stands including biodiversity protection. This is the widespread paradigm in Europe. Through Closer-to-Nature Forest Management the managed forest can contribute to biodiversity protection outside the protected forest.

Maintaining or restoring the different components, structures and functions that safeguard long-term health and functionality and that support biodiversity in forests and woodlands requires concepts to be applied to different spatial (stand, forest patch, landscape) and hierarchical scales (genes, species populations, communities, ecosystems). Europe's forests and woodlands are diverse. With a history of over 6,000 years of intensive interaction between man and nature, European landscapes and forests support important social, economic and biological values (Nocentini and Coll 2013). In particular, the biological legacies (e.g. old trees and specific tree species) provided by a number of historical management methods such as coppice forest, coppice with standards, wood pastures and forest meadows harbour much biodiversity (Bürgi et al. 2020; Schütz 1999). Strategies and benchmarks for biodiversity conservation thus include both naturalness and traditional cultural woodlands managed by small-scale or peasant farmers, traditional livestock keepers/pastoralists (Knight 2016; Angelstam et al. 2021). Similarly, a wide range of approaches for integrating conservation measures in forests managed partially or primarily for wood production has been developed. These include Close-to-Nature Forestry, Continuous Cover Forestry, Retention Forestry, Mimicking Natural Disturbance, Emulating Natural Processes, Ecosystem Management, Ecological Forestry. They are inspired by the structures and successional trajectories observed in natural forests in their respective region (Angelstam 1996; Kuuluvainen et al. 2021; Sotirov et al. 2020; Puettmann et al. 2015; Gamborg and Larsen 2003, 2005; Pommerening and Murphy 2004).

In addition, a wide range of nature-near approaches are under development to support forest health and not least the adaptation of forest and forest landscapes to climate change and other external (global) threats e.g. climate smart forestry (Bondwitch et al. 2020; Seppälä 2009; Li et al. 2011; Gauthier et al. 2015; Spathelf et al. 2018; Weatherall et al. 2022).

Definition of Closer-to-Nature Forest Management

We define Closer-to-Nature Forest Management as an overarching "umbrella" covering all approaches and terminologies which under the auspices of Sustainable Forest Management (SFM) support biodiversity, resilience and climate adaptation in managed forests and forested landscapes. Closer-to-Nature Forest Management will promote components, structures and processes characteristic of natural forests and cultural woodlands, thereby improving diversity of tree species and structures, variation in tree size and development stages, and a range of habitats including habitat trees and dead wood.

Consistent with this, we define the following underlying principles of Closer-to-Nature Forest Management:

- Retention of habitat trees, special habitats, and dead wood
- Promoting native tree species as well as site-adapted non-native species
- Promoting natural tree regeneration
- Partial harvests and promotion of stand structural heterogeneity
- Promoting tree species variation and genetic diversity
- Avoidance of intensive management operations
- Supporting landscape heterogeneity and functioning

In the following sections these principles are presented in the context of already existing nature-based forest management concepts and further analysed and discussed regarding their capability to support biodiversity, forest health and adaptation.

2. Origins and present status of nature-based forest management in Europe

Although Closer-to-Nature Forest Management is an overarching "umbrella" term, the idea "to follow and support nature" is not new in forestry. The following sections give a short overview of the different traditions and current practices regarding nature-based forest management (NBFM).

Historical development

The historical impetus for the development of NBFM in Europe has mostly been a response to land degradation, such as deforested and overgrazed karst and heath landscapes (Froment 1978; Gams 1993), many overcut forests, erosion-exposed mountain regions, lowland regions threatened by flooding, and negative experiences with even-aged conifer plantations (Gayer 1886; Agnoletti and Anderson 2000; Paletto et al. 2008). However, the growing importance of forest conservation and aesthetics also influenced the evolution of NBFM (Hufnagl 1939; Johann 2003), as did the successful afforestation of some Mediterranean regions (Kranjc 2009; Cervera et al. 2019), the improvement of degraded forests with continuous cover forestry (Möller 1922), as well as experience with the coppice with standards system and regulated selection systems (Schütz 2001a).

In most cases, however, the selection system was not regulated for forest sustainability and often resulted in forest degradation by repeatedly extracting the most valuable trees, leading to initial opposition from the forestry profession and governments (Schütz 1994). However, in forests with cautious owners, well-regenerated, structured and high-quality stands were cultivated. With the development of a continuous inventory system in many parts of Europe to check success (the 'Control Method'), the selection system was put on a sustainable basis and increasingly accepted and developed by the forestry profession (Gurnaud 1885; Biolley 1901).

This represented a new paradigm in forestry that emphasised the importance of adapting measures to forest response and focusing on the remaining stand after logging. Most early protagonists had a shared holistic understanding of the forest as a complex system and advocated site- and stand-adapted management, in contrast to today's often stereotypical perception of uneven-aged forestry as being restricted to a selection system without considering other silvicultural systems (Pfeil 1860; Engler 1900; Biolley 1901; Möller 1922). In parts of Atlantic Europe, interest in alternative silvicultural regimes began in the last century (Troup 1927; Anderson 1960) and in the 1950s resulted in large-scale trials of European nature-based silvicultural systems which continue to provide useful results (Kerr et al. 2010).

After World War II, the development of forest management in temperate Europe was influenced by the initiation of old-growth research, which was to serve as the basis for NBFM, the introduction of forest reserves, intensive studies of forest sites and the development of multipurpose forest management (Leibundgut 1959; Ellenberg 1988). This was made possible by increased trans-European cooperation and the establishment of national and international organisations to support NBFM (ANW, Pro Silva). The result was a refinement of NBFM that focused on a holistic combination of variable silvicultural systems and other management tools according to multipurpose objectives (Leibundgut 1943; Susmel 1980; Korpel 1995; Mlinsek 1996). In Atlantic Europe, new forest policies (e.g. in the UK) gave much greater emphasis to multifunctional management and resulted in increasing interest in management that avoided the visual and ecological disruption caused by clear felling. This approach has become known as Continuous Cover Forestry (CCF) (Mason et al. 2021).

In addition to significant advances, the development of forest management in the second half of the 20th century was also characterised by shortcomings, such as a focus on stand-level processes and a lack of consideration of historical disturbance regimes (Angelstam 1998). Founded in 1989, the Pro Silva association, which promotes NBFM through the exchange of knowledge and best management practices, has contributed significantly to the gradual expansion of alternative forms of forest management to industrial forestry in Europe (Mason et al. 2021).

In the boreal forest, the turn of the century brought a series of studies on natural disturbance regimes and guidelines on how to incorporate them into forest management to support biodiversity conservation (Kuuluvainen 1994; Angelstam 1998; Splechtna 2005; Koivula et al. 2014; Berglund and Kuuluvainen 2021). In recent decades, medium to large scale disturbances across central and eastern Europe have shown the necessity to think about including into forest management forests affected by bark beetle, ice sleets, snow breakage, landslides, windthrows, fires and droughts (Gardiner et al. 2013; Kulakowski et al. 2017; Schelhaas et al. 2003; Hlásny et al. 2019, 2021; Senf and Seidl 2021). In contrast to the 'ship's wake theory' that assumed that maximum production automatically optimized ecological and social benefits (Glück 1987), there is a growing awareness of the importance of ecological continuity and biological legacies and specific conservation measures (Scherzinger 1996; Motta 2020). In many European countries improved forest governance systems based on participation and transparency have enabled the introduction of new management tools and the development of consensual, binding solutions for all parties involved in forest management (Simoncic et al. 2015; Eigenheer et al. 2016). In other regions, however, there is considerable resistance towards alternatives to even-aged forestry (Hertog et al. 2022).

Current practice in Europe

In Europe, depending on the region and the portfolios of stakeholders and actors, there are different views on the NBFM approach and ways of implementing it, although the definitions and the main paradigms are similar. These different approaches have been developed in response to varied settings in different regions (Angelstam et al. 2011). This makes transferring successful approaches to other regions challenging, as it requires site- and region-specific adaptation (O'Hara et al. 2018; Krumm et al. 2020).

The modern definition of NBFM considers forests as complex ecosystems, advocates management based on natural processes, attempts to integrate many forest functions at small spatial scales, and applies variable management approaches, most commonly low-impact harvesting, which means minimising negative impacts on regeneration, the remaining stand, and whole forest ecosystem (Leibundgut 1990; Mlinsek 1996; Schütz 1999; Mason et al. 2021). Special emphasis is placed on maintaining the integrity of forest microclimate and soil; thus clear-cutting, intensive soil preparation and the use of fertilizers and herbicides are generally avoided. NBFM is synonymous with continuous cover management in Atlantic Europe, close-to-nature management in Central Europe, and forest ecosystem management in the USA (Puettmann et al. 2015).

At present NBFM is practiced on 22-30% of forest area in Europe, however, this area is gradually but steadily increasing due to environmental, economic and social factors (Mason et al. 2021). The proportion of forests where NBFM is practiced ranges from a few percent in Portugal, Finland and Sweden to almost 100% in Switzerland, Slovenia and some German states where this approach is required by forest law. In Denmark NBFM is based on Close-to-Nature forest management principles and is obligatory in all public forests (Larsen 2012).

Practical approaches in the field also differ, with some NBFM proponents only advocating selection management, while most NBFM advocates and practitioners employ a variety of silvicultural tools, including clearcutting in rare cases, and focus on tailoring interventions to site ecology, stand conditions and management objectives (Schütz 1990; Fries et al. 1998; Boncina 2011b). Research on historical disturbance regimes in temperate forests indicates that small and intermediate disturbances are important, while in regions with a slower organic matter cycle, disturbances of higher intensity are more vital, e.g. fires and bark beetle calamities (Nagel et al. 2013a; Čada et al. 2016). Research suggests that nature-based silvicultural systems are consistent with historical disturbance regimes of forest ecosystems (Nagel et al. 2014), while mimicking stand replacing disturbances in other sites is constrained by forest health or direct protective functions of the forest.

The implementation of NBFM and monitoring takes place through participatory forestry, through the implementation of Natura 2000 legislation or based on landscape planning, and with the support of public forest and nature protection services (Stringer et al. 2006; Bouwma et al. 2018; Angelstam et al. 2020). There are significant differences between European countries, as in some places planning is largely left to forest

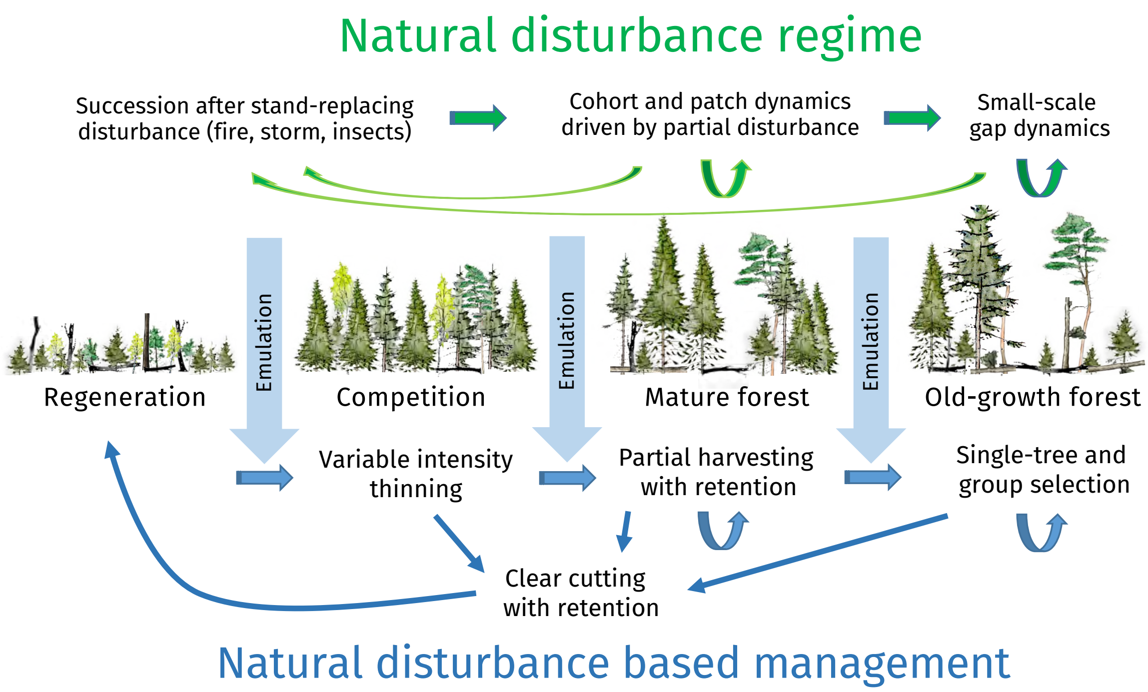

Figure 2: Illustration of how the understanding of natural disturbance regimes can guide natural disturbance-based management. The forest successional sequence after stand-replacing disturbance is divided into four developmental phases, with their typical internal dynamics. Silvicultural tools are used in each phase to emulate natural disturbances. The retention of ecological legacies (living and dead trees) is applied in regeneration cutting, variable-density thinning is used to emulate competition-phase dynamics, partial harvesting and high-retention cutting can be used to imitate group dynamics and opening up of the canopy, and structure and dynamics of old forests are emulated by selective and group harvesting. The desired proportions of developmental phases are ideally derived from a reference landscape or from the historical reference-disturbance regime (modified from Kuuluvainen et al. 2017, 2021).

owners, while in others it is well developed and involves forest owner at the regional level (Bouriaud et al. 2015; Eigenheer et al. 2016). In several Alpine regions, for example, the Forest Service provides free advice including even tree marking, which represents an opportunity for nature conservation on the ground by protecting rare habitats, favouring rare species and habitat trees (Adamic et al. 2016; Krumm et al. 2020).

In the UK and Ireland, discussion about the desirability of using NBFM on a wider scale is increasing (Mason 2021; Vitkova et al. 2013), but the uptake of this is still low. Constraints include: the length of time required to transform the existing simple forests to more resilient diverse structures; the need for both public subsidies for forestry and certification schemes to be designed to accommodate the transformation period; plus the need to adapt silvicultural methods devised in other European regions to forests dominated by non-native species and climates where wind is the main natural disturbance process (Quine et al. 1999). When introducing NBFM approaches to British and Irish forest management, a key requirement for success is the installation of and continued funding for a network of documented long-term trials with supporting research which can provide guidance for developing best practice and allow local learning (Lawrence 2017). Examples of such trials exist in forests dominated by Sitka spruce and other non-native species in both the UK and Ireland.

Conceptual approaches to NBFM and practice in boreal forests differ from those in temperate Europe (Angelstam 1998; Kuuluvainen et al. 2021; Laiho et al. 2011). European boreal forests are naturally characterised by diverse disturbance dynamics including partial, small-scale and large-scale disturbances (Angelstam and Kuuluvainen 2004; Kuuluvainen and Aakala 2011; Berglund and Kuuluvainen 2021). However, current forest management does not reflect this variation adequately. Clearcutting is the dominant harvesting method and biodiversity conservation is mostly based on the protection of key habitats and leaving of retention trees (Gustafsson et al. 2020a). For decades the main approach to emulate natural disturbances in the boreal production forest has been retention of a certain share of living trees and tree groups, as well as retention of dead wood at final harvest. However, the levels of retention are generally low considering effective biodiversity conservation (Angelstam et al. 2021; Kuuluvainen et al. 2019). In European temperate forests, due to long and intense human impact, research about natural disturbance regimes is more difficult (Bebi et al. 2017; Vacchiano et al. 2017) as well as the development of the awareness of its importance. At the same time natural disturbances have become a major part of forest planning, though unintentionally. This forces managers to use the opportunity to incorporate disturbed areas into forest management and thus contributes to providing forest structures that are important for nature conservation (Hlasny et al. 2021; Thom and Seidl 2016; Zimova et al. 2020).

Other measures include restoration actions on new protection areas or on areas voluntarily set aside due to forest certification requirements. These actions include, for example, removing spruce to benefit broadleaved trees, creating gaps, restoring hydrology by closing ditches and clearcut or partly harvested areas to simulate the effects of wildfire (Halme et al. 2013). Currently, in the boreal forest there is increased interest and research in replacing clearcutting with continuous cover management for more diverse provision of ecosystem services (Tahvonen 2009; Peura et al. 2018; Pukkala 2018). For example, in Finland continuous cover management was again allowed in the 2014 Forest Law. Still, there may be challenges to maintain the shade-intolerant Scots pine *Pinus sylvestris* and avoid increased dominance of the shade-tolerant Norway spruce *Picea abies* (Pukkala et al. 2012). However, in the forestry sector in Sweden and Finland, culture and education, industrial forestry networks and timber markets promote clearcut forestry, and there is considerable resistance towards adopting continuous forest cover approaches (Angelstam et al. 2022; Hertog et al. 2022).

Throughout the Mediterranean region, overexploitation and depletion of forest resources have had a profound impact on the ecosystems (Vogiatzakis et al. 2006). The basic principles of NBFM are also appropriate for Mediterranean forests and there are many examples of uneven-aged management (Grassi et al. 2003; Trasobares and Pukkala 2004; Diaci et al. 2019), although processes such as deforestation, overgrazing and soil degradation with desertification, replacement by shrubs and fire-prone secondary conifer plantations must be considered. More than 95% of fires are caused by human activities, making societal measures essential (e.g. Keeley et al. 1999; Syphard et al. 2009; Malak et al. 2015). To reduce the occurrence and severity of wildfires, various practices and tools should be used such as prevention, regulation, surveillance, landscape planning, forest management and public awareness.

Silvo-pastoral systems exist as a land-use type in some areas of the Mediterranean (e.g. dehesa and montado) and are found in oak woodlands in other parts of Europe and in larch woodlands in the Alps (Garbarino et al. 2011). These semi-artificial systems are characterised by an open canopy, low tree cover and simplified stand composition and structure, combined with the production of pasture for livestock or crops. They are also traditionally associated with some old 'veteran' trees providing naturalness at the micro-scale. The silvo-pastoral system as it exists today was introduced and promoted on a larger scale starting in the mid-19th century (González Vazquez 1944). Evidence suggests that these cultivated agro-forests support a high diversity of plants and animals, mostly associated with the grass layer component (Aragón et al 2010; Angelstam et al. 2011). However, they also face a number of ecological problems, such as lack of natural regeneration, tree decline, soil degradation and pest and disease incidence (Brasier 1996; Santos and Tellería 1997).

The Mediterranean region has a set of weaknesses regarding forest management that require greater attention and support. The lack of a structured timber sector makes a planned and rational forest management process difficult, being a vicious cycle. NBFM offers several beneficial possibilities, namely related to soil, water, microclimate, biodiversity, climate adaptation, pests and diseases, fires, forest production, landscape, income, tourism, health and wellbeing of human communities (Croitoru 2007).

Although there is abundant experience of NBFM across European forest landscapes, there is still a lack of robust and long-term data on NBFM available for research and implementation (Mason et al. 2021). Consequently, a joint European initiative to bring together existing regional data is urgently needed.

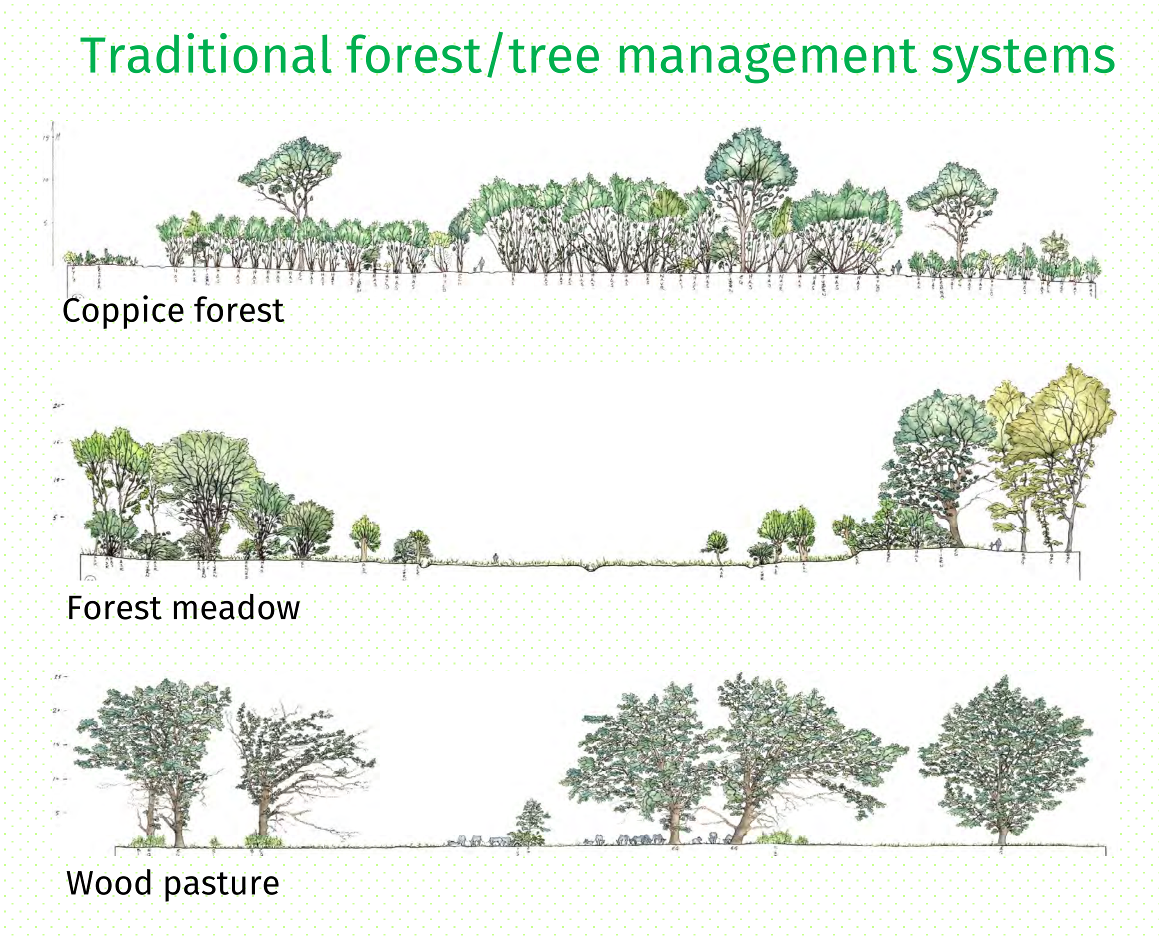

Figure 3: Some traditional forest and tree-based management systems (from Larsen 2012). Coppice forests, forest meadows and grazing forests contribute to biological diversity, and have been diminished in some parts of Europe. Their integration in the forest landscape would contribute to habitat variation and biodiversity conservation/protection.

Furthermore, the ability of NBFM to provide a wide range of public goods and services is poorly recognised. This lack of appreciation is reflected in the absence of adequate subsidies to compensate owners for the less careful interventions needed to enhance biodiversity.

The decision to adapt the current forest management approaches to various forms of NBFM involves different drivers and multiple challenges in different parts of Europe and should ideally also consider a range of spatial scales.

3. Biodiversity and forest management

Biodiversity is the variability among genes, species and ecosystems, and changes therein can influence the supply of ecosystem services. Biodiversity has also cultural, ethical, non-monetary values that contribute to human wellbeing and welfare (Szaro and Johnston 1996; Hunter et al. 2014; IPBES 2019; Gossner and Wohlgemuth, 2020; Piras et al. 2021).

Forest-dwelling species and their genetic variation have evolved over thousands or even millions of years, being adapted to the environmental conditions before the Anthropocene. Thus, insights into past patterns and processes at multiple scales offer guidance on how to maintain natural forest ecosystems and their associated species and genetic variation.

Plants, animals, fungi and single-cell organisms interact and are foundations for ecosystem functions and processes (Science for Environment Policy 2021). The provisioning of ecosystem services such as wood production, water purification, carbon sequestration and recreation, and maintenance of multifunctional forests, depend on well-functioning species and species interactions (Krumm et al. 2020). For example, most trees need symbiotic association with fungi (mycorrhiza) to aquire nutrients, and bees and wasps, butterflies, beetles, moths and hoverflies pollinate many herbaceous plants on the forest floor (Kraus and Krumm 2013).

Research indicates that maintenance of genetic, structural, and functional diversity in forest communities forms a good basis for multifunctional and sustainable forest use (Kraus and Krumm 2013). Soil biodiversity is less known but fundamental to the functioning of terrestrial ecosystems through interactions with above-ground biodiversity (Nielsen et al. 2015; Guerra et al. 2020). The intensity, frequency and spatial extent of natural disturbances such as droughts, fires, storms, floods and insect outbreaks have been instrumental in determining forest structure and the distribution of organisms on trees, in stands and across landscapes (Kuuluvainen et al. 2021). This spatial dependency makes separation of biodiversity at different scales important. For species these scales are often referred to as alpha (sites), beta (among sites) and gamma (landscape or other higher unit) diversity.

An important principle for the conservation of species in a landscape has the acronym 'BBMJ' (Lawton et al. 2010), where BBMJ stands for Better (quality), Bigger (patch size), More (quantity) and Joined (functional connectivity). Validation of habitat models for various species demonstrates the important role of sufficient amounts of habitat networks that satisfy all these criteria (Angelstam et al. 2020). Ultimately habitat amount is a key factor (Fahrig et al. 2013; Watling et al. 2020). The contrasting natural disturbance regimes over Europe to which species are adapted are likely to have affected species' dispersal abilities. In regions with large-scale and intense disturbances, such as fire, species are probably comparatively easily dispersed, and connectivity consequently is rather unimportant. In contrast, in regions with less frequent and small-scale disturbances, such as from wind disturbance or limited pest outbreaks, dispersal capacity is likely to be smaller, and connectivity is more important.

The importance of disturbances for biodiversity also implies that not only recently disturbed areas but also their consequences (old trees and dead wood in different decay stages, as well as more open forests), provide an abundance of habitats for many species (Swanson et al. 2014; Hilmers et al. 2018). Between 20 and 40% of forest plants, animals and fungi have been estimated to depend on dead or dying wood, at some point in their life cycle (Bauhus et al. 2019).

Traditional forest management systems such as coppice and coppice with standards, and also agro-silvopastoral practices such as grazing, haymaking, and the promotion of a rich variation in tree species have contributed to sustain specific habitats of value to many organisms (Horak et al. 2014; Unrau et al. 2018; Mantero et al. 2020; Johann 2021). Biological and cultural diversity intervene together in many European landscapes, combining historical and natural processes (Targetti et al. 2014; Bürgi et al. 2015). This also has implications for biodiversity and Closer-to-Nature Forest Management since many landscapes are multifunctional. When implementing forest management approaches, it is also important to take into consideration the effects of cultural aspects on biodiversity, understanding how these links affected species and habitats, and interpreting the relationships between cultural and biological diversity, considering landscape functions (Turner et al. 2007). The landscape in many European regions has a dynamic nature, and changes are the result of interacting natural and cultural factors that often act over different temporal scales, and where traditional activities may also change over time (Antro 2006). Some landscapes often present a high level of habitat diversity related to a mosaic produced by the application of different management regimes. In some cases, cultural and diverse landscapes were often managed by small-scale farmers and owners. The growth of new forests in Europe has often created homogeneous forest cover with little spatial diversity, contributing to the loss of biological and cultural values. On the other hand, there might be a need to conserve key habitats resulting from the reciprocating influences between people and nature (Adams 2003; Carver 2014). Therefore, a broader landscape approach allows consideration of the integration of environmental, economic, and social systems.

External and internal pressures on species and habitats

Over millennia there has been an extensive transformation of European forests and woodlands to agricultural and urban landscapes (Jepsen et al. 2015), decreasing the potential natural forest cover from an estimated 80% of the European land area to the current 35% (EEA 2020; Forest Europe 2020). The reduction in forest area as well as forest use and environmental impacts have led to a variety of pressures on biodiversity. These pressures can be classified as *internal* (different forest management activities) and *external* (impacts such as climate change, eutrophication, and biological invasions) (Table 1).

As a result of past and current pressures the proportion of primary and old-growth forests, i.e. forests with limited human impact, is only a mere 2-3% of the original total forest cover (Forest Europe 2020; Barredo et al. 2021; O'Brien et al. 2021), demonstrating the strong long-term reshaping of forest landscapes. Another trend is a continuous decrease in traditional silvo-pastoral management practices, due to more intensive and large-scale agriculture, and the sharp population decline in remote rural areas (Bürgi et al. 2020). Multiple anthroprogenic pressures have caused a decline in many forest plants, animals and fungi, exemplified by 10% of mammals, 10% of reptiles, and 8% of the amphibians in forests in the EU being at risk of extinction (EEA 2016).

How forestry aimed at wood production affects biodiversity

All forest management actions aimed at wood production affect the structure of forests, alter the number and variability of habitats and change the landscape structure, and affect biodiversity at different scales (Gavin et al. 2021) (Figure 4). This leads to changes in species composition and species interactions, and reduces the dispersal ability of many organisms compared with the natural forest landscapes to which native species have adapted (Schulze et al. 2009, Chaudhary et al. 2016, Thorn et al. 2020). The intensity of forest operations varies strongly locally as well as regionally in Europe. Intensive forestry operations with potentially the most negative impact on biodiversity include: regeneration creating dense and structurally homogenous tree monocultures; soil cultivation and compaction; and the use of chemicals including pesticides, herbicides, nitrogen and other fertilizers.

Conservation actions and Closer-to-Nature Forest Management

Closer-to-Nature Forest Management implies that actions to promote biodiversity within managed forests are reinforced. Such actions are of several types.

First, a key action is to retain at harvest (i.e. leave behind) living and dead trees of special importance to plants, animals and fungi, for instance very old trees, rare tree species, trees rich in micro-habitats and dead trees of large dimensions (Krumm et al. 2020; Thorn et al. 2020a; Lachat et al. 2013; Scherzinger 1996). Tree patches and unusual biotopes may also be set aside. Retention actions are relevant to the whole range of forest management types from clearcutting forestry to Closer-to-Nature Forest Management (Gustafsson et al. 2020). Forest areas or patches affected by natural disturbances should be included in forest planning.

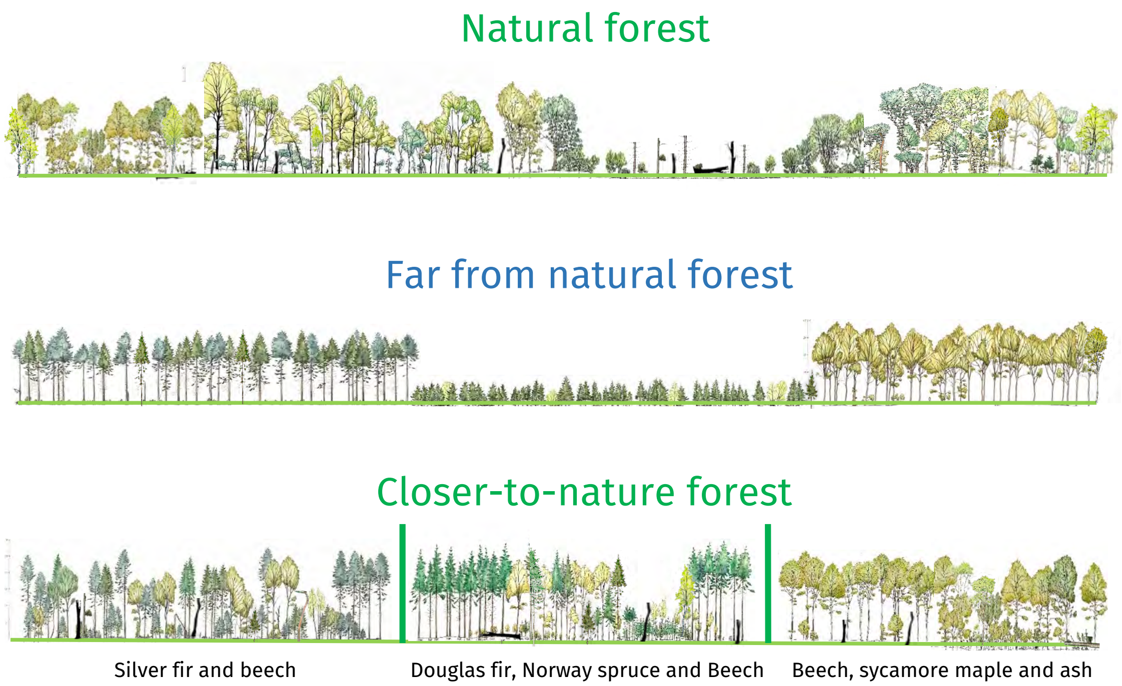

Figure 4. A natural forest (upper panel), a forest intensively managed for wood production (far from natural state) (middle panel) and a forest managed with Closer-to-Nature methods (lower panel). This representation is highly generalized and does not capture the large variation in forest zones and landscape types of Europe. There are many types of forest management approaches in Europe leading to forest states with more or less strong similarity to natural forest. The lower panel (Closer-to-Nature forest) presents three examples of Forest Development Types (FDT) described and illustrated in Larsen (2012). Left - Silver fir and beech managed through selection cutting; centre - Beech with Douglas fir and larch, and right - Beech with ash and sycamore maple both managed through group selection.

Table 1. Main pressures on biodiversity (plants, animal and fungi) caused by forestry focusing on wood production (internal pressures) and other factors (external pressures), and their consequences for biodiversity.

Internal pressures (forestry for wood production)	Consequences for biodiversity
Harvesting of old-growth forest	Reduces populations of species largely confined to more or less undisturbed and continuous tracts of old forest with high structural variation.
Removal of old, dead and dying trees	Disfavours species depending on big and old trees displaying a wide range of tree-related microhabitats such as hollows, crevices and wounds as well as standing dead wood of different sizes and decay stages and corresponding microhabitats.
Clearcutting with extraction of all trees	Negative for species sensitive to large open areas, including those that need a stable forest-interior climate. A more long-term effect is a dramatic decrease in old trees and dead wood.
Treatment of disturbed forest areas	Disturbances provide forest development stages that are often rare in managed forest landscapes. Structures created by specific disturbance agents (fire, storms, beetles) attracts specialists (e.g. semi-burned trees, root plates or splintered stems) and provide habitat for many species. Complete removal of dead trees prevents colonization of saproxylic species. Fast reforestations hinder the occurrence of numerous specialist species e.g. ruderal and thermophile species.

Table 1. continued.

External pressures (outside of forestry)	
Intensive site preparation	In addition to organic matter removal, soil perturbations and fertilizer additions, which can affect soil animal and microbial communities, the control of ground vegetation through herbicides or mechanical means reduces plant species richness and hence diversity of insects and provision of related ecosystem services.
Forest type and habitat conversion	Variation in forest types and habitats is fundamental to a rich biodiversity. Forestry impacts tree-species composition, structural and horizontal variation, tree and forest stand ages and alters hydrology. Often small, deviating habitats are removed and transformed into production forests. Thus, conversion of forest has considerable effects on species composition and may cause decrease and loss of species adapted to natural forest landscapes.
Maintenance of dense forests with high growing stocks	High wood volumes imply darker and denser forests with negative response of light-demanding species, many of which are becoming less common today. Higher sensitivity to human-induced disturbances.
Introduction of non-native or poorly adapted species/provenances	The use of introduced tree species and ill-adapted provenances may lead to changes in ecological processes such as nutrient dynamics, in turn affecting plants, animals and fungi.
Abandonment of traditional forest management approaches (coppice, coppice with standards, wood pasture systems)	The abandonment of traditional practices in many parts of Europe leads to a habitat loss for specialized species of cultural landscapes and open agro-forest conditions.
Climate change	The distribution of species will alter, vulnerable habitats will be lost, species interactions (competition, mutualistic relationships, pests and diseases) will be affected and altered disturbance patterns will change habitats.
Landscape fragmentation	Functional connectivity of a region's forest types is fundamental to long-term maintenance of species and species communities.
High populations of large herbivores. Since forest management partly controls their food resource, they are regulated both by external and internal factors	Herbivores such as deer and moose cause browsing and fraying damage to young trees, which precludes preservation/restoration of less common tree species hosting a rich associated biodiversity.
Eutrophication through nitrogen deposition	Nitrogen addition to forest soils through the atmosphere disadvantages species adapted to nutrient-poor soils, most marked for ground- vegetation but with side-effects for associated species.
Biological invasions	Extinction cascades may be trigged if invasive plants, pests and pathogens are introduced; this may lead to the loss of tree species, which can have a considerable impact if such trees host a rich associated biodiversity with many rare species.

Literature sources: Addison et al. 2019; Bernes et al. 2018; Bernhardt-Römermann et al. 2015; Carpio et al. 2021; EEA 2020; Fahrig 2003; Fedrowitz et al. 2014; Götmark 2013; Gundale 2021; Košulič et al. 2021; Krumm and Vítková 2016; Liebhold et al. 2017; Lindenmayer and Laurance 2017; Lindner et al. 2013; Milad et al. 2011; O'Brien et al. 2021; Plue et al. 2013; Pötzelsberger et al. 2021; Stokland et al. 2012; Thorn et al. 2018, 2020b; Thom and Seidl 2015, 2016; Unrau et al. 2018; Verheyen et al. 2012; Vilén et al. 2016.

Especially in a future of increasing uncertainty, disturbed areas might provide valuable and rare habitats and capacities for threatened species dependent on deadwood, light, ruderal patches and special forms (Thorn et al. 2018). Disturbances are an inherent, integral part of ecosystems and are anyway essential for the promotion of habitats for threatened species (Gunderson 2001).

Second, ecological processes may be reinforced and/or reinstalled by allowing for and promoting natural regeneration and tree species diversity, thereby restoring forests to desired states (Schütz 2002; Hahn et al. 2005; Bauhus et al. 2009; Mairota et al. 2016; Kirby et al. 2017; Krumm et al. 2020; Vymazalová et al. 2021). This also includes the avoidance of intensive site preparation techniques such as soil perturbation, herbicide application and use of fertilizer. Instead, where possible, natural structures and processes such as the presence or development of ground vegetation or shrubs may be used to facilitate establishment of tree regeneration (Gómez-Aparico et al. 2004). Specific actions can also be taken to restore special habitats, for example restoring drained wetlands/mires (Andersen and Krog 2020) or specifically in boreal Europe to introduce prescribed burning at certain sites (Lindberg et al. 2020).

Third, forest management can be used as a conservation tool to maintain and restore properties associated with former agricultural woodland practices such as creating gaps to mimic forest meadows with inner forest edges and transition zones, and to maintain traditional management such as coppice and coppice with standards (Götmark 2013; Cutini et al. 2021).

Fourth, restoration measures are sometimes actively applied to individual trees, to create tree-related microhabitats (e.g. cavities, wounds, breakages), to mimic growth patterns of slow-growing, suppressed trees or by killing trees to increase the amount of dead wood, e.g. creating high stumps or girdling (Krumm et al. 2020).

The impacts of forest management practices and the progress towards desired outcomes can be evaluated using indicators. An analysis addressing different ecological hierarchical scales from stand to landscape and regional level may be used. This puts together tree characteristics and functions, forest stand dynamics and ecological succession with forest landscape ecology, considering their interrelations and dependencies. Forest dynamics and spatial variability are closely linked, involving the effects of biological processes and external factors, which occur at a wide range of spatial scales (Hooper et al. 2002; Jax and Roozi 2004). A set of criteria and indicators can be used to evaluate the effects of management options on forest development over time (Karvonen et al. 2017; Nabuurs et al. 2018; Santopuoli et al. 2021). Structural features, tree species composition, tree regeneration, naturalness, carbon stock and related ecosystem services, as well as social and cultural values might be used as some of the most important indicators.

4. Global change pressures, forest health and adaptation

Global change poses various challenges, including climate change pressures, biodiversity loss, nutrient enrichment in some places, but also depletion in others (DeFries et al. 2012) as well as invasive alien pests (Seidl et al. 2018). Forests can help mitigate some of those problems by providing nature-based solutions (IUCN 2021).

However, while being part of the solution, forest landscapes' service provision is threatened by global change. For example, increasing disturbances can compromise important ecosystem services (Thom and Seidl 2016), including substantial decreases in the carbon storage potential of Europe's forests (Seidl et al. 2014; Collalti et al. 2019). Invasive exotic pests and diseases, facilitated by both climatic changes and increasing global trade, threaten biodiversity and the functioning of ecosystems (Aquilué et al. 2021). Seidl et al. (2018) estimate that 10% of the carbon stored in Europe's forests is at risk from the effects of five detrimental alien pests. On top of these impacts, extreme weather events, such as the summer drought of 2018 in Central Europe (Schuldt et al. 2020), may lead to gradual or abrupt regime shifts. Communities and industries relying on forest goods and services may have to adjust to such changes taking place, affecting the type of forest management, the portfolios of ecosystem services (productive characteristics) and adaptability (Adger et al. 2003). The mitigation and adaptive capacity offered by a certain type of forest management is therefore an important feature/aspect of climate change pressure and adaptation.

Nature-Based Forest Management (NBFM) (see section 2) is considered among the most prominent nature-based solutions (IUCN, 2021) to adapt future forests to global change pressures and ensure their ecosystem service provisioning. For example, Brang et al. (2014) identified various principles qualifying close-to-nature forest management as a suitable strategy to adapt forests to climate change. We consider here our seven slightly revised principles (compared to Brang et al. 2014) of Closer-to-Nature Forest Management (see section 1) and assess them in light of their impact on *resistance*, *resilience* as well as *adaptive capacity* (Larsen 1995; Oliver et al. 2015; Figure 5).

For example, we consider 'Partial harvest and promoting stand structural heterogeneity' as a means to improve the resilience of forests, e.g. through establishing young tree cohorts in canopy gaps. In addition, 'Promoting tree species variation and genetic diversity' is a good method to improve the adaptive capacity of forests, and 'Promoting native tree species as well as site adapted non-native species' should help achieve a high forest resistance to disturbance.

Retention of habitat trees and dead wood

An important measure to enhance the restoration capacity of a forest after disturbance is to retain a significant amount of ecosystem legacies (e.g. seed trees, dead wood, stand remnants), thus increasing the structural diversity of stands (Seidl et al. 2014; Johnstone et al. 2016; Jõgiste et al. 2017; Spathelf et al. 2018). Legacies provide seed dispersal, nutrient translocation, water storage, and the maintenance of genetic information in the recovery phase of an ecosystem after disturbance (Bauhus et al. 2009; Drever et al. 2006). Moreover, stand-level legacies contribute as an important habitat to faunal species richness, e.g. for antagonist species which can curb biotic disturbances. Therefore, legacies increase the number of potential pathways for ecosystem restoration after disturbance. This fits well with the general goal to manage forests for resilience. The retention of habitat trees and deadwood with a focus on Tree-related Microhabitats (TreMs) has become important in forest management (Larrieu et al. 2018; Bütler et al. 2020).

Promoting native tree species as well as site-adapted non-native species

Native and site-adapted introduced (non-native) tree species dominate the tree species composition in common European Close-to-Nature forest strategies (Duncker et al. 2012). Native tree species and the species that they host have generally undergone an extensive selection process through evolution and are well adapted to the previous or current site conditions and natural disturbance regime (Figure 5), although this might not provide enough adaptive capacity under climate change. Mixing native or site-adapted tree species with exotic species to obtain semi-natural, possibly future natural forests (Peterken 2001) may enhance the adaptive capacity of the forests (Vitali et al. 2018), where the resistance of the exotic tree species (e.g. Douglas fir) may benefit from the native tree species admixture (Brandl et al. 2020). As an additional benefit, semi-natural forests also reconcile biodiversity conservation with timber harvesting objectives (Lõhmus et al. 2016).

Promoting natural tree regeneration

Natural regeneration is advantageous where the native parent trees are site-adapted, have a high genetic diversity and have other desirable qualities (e.g. good form). However, in some situations, particularly in established stands with introduced tree species, the composition needs to change to adapt forests, or there may be better adapted provenances that should be introduced. For example, selecting provenances from areas where there are more severe droughts may favour drought resistance of trees.

The genetic diversity of current stands may be quite low, either because the population went through bottleneck situations in refuge populations during the last glaciation (e.g. European silver fir, Bergmann et al. 1990) or where secondary forests were established in the past without consideration of genetic origin and diversity. In these cases, using assisted migration by enrichment planting to introduce a proportion of better adapted planting stock (Williams and Dumroese 2013) is more sensible than waiting for natural selection to take place, given the rapidity of climate change and the length of time it will take for natural regeneration to occur. Stand conditions may also be improved by planting native trees, mixed provenances as well as introduced species in mixtures with natives.

Partial harvests and promotion of stand structural heterogeneity

Structurally diverse forests hold potential for enhanced forest resistance, probably including resistance to invasive alien pests (Seidl et al. 2018) although directly after partial harvest or thinning their resistance may drop (Maringer et al. 2021). Structural heterogeneity at the stand scale supports high forest resilience and adaptive capacity (Figure 5). Mixing trees of different dimensions in uneven-aged, structured stands can achieve similar effects to mixing species (see below) (Dănescu et al. 2016). However, these effects have been much less systematically studied and conflicting results exist. In any case, uneven-aged stands with already present regeneration increase forest resilience if, as in the case of storms or drought, the advance regeneration is less affected by the disturbance. This method of increasing resilience through advance regeneration is possible both with shade-tolerant and intolerant tree species, depending on the gap size used for regeneration.

Elevated resistance and resilience of structurally heterogeneous forests was shown in both empirical economic studies and models. For example, Hanewinkel et al. (2014) found reduced vulnerability of uneven-aged forests to natural disturbance. In a recent modelling study, Malo et al. (2021) have demonstrated the economic advantage of a structurally diverse continuous cover forest to cope with natural disturbances in boreal spruce-pine forests. Knoke et al. (2021b) showed faster recovery of economic value of structurally heterogeneous forests, underlining their high resilience potential after high severity disturbance. A further attractive feature of structurally heterogeneous forests is their elevated carbon storage, which they provide to society as a positive externality (Knoke et al. 2020).

Promoting tree species variation and genetic diversity

Various empirical studies have shown higher resistance of mixed forests than of single-species forests against natural hazards, both without (Griess et al. 2012) and with consideration of climate change (Neuner et al. 2015; del Rio et al. 2017). This effect of mixtures at the stand or landscape level is due to: (a) ecological insurance, as the presence of functionally diverse species increases the likelihood that some species can cope with stress and disturbance (Yachi and Loreau 1999) and (b) species interactions, which change the way an individual species responds to stress and disturbance, so that it may be more or less resilient in mixtures than in pure stands (Bauhus et al. 2017c). For example, a recent study used a pan-European dataset and showed that Norway spruce and Douglas fir are much more resistant to disturbance (e.g. wind, bark beetles, snow breakage) in particular in a warmer and drier climate, when embedded in a mixed forest (Brandl et al. 2020). There are other positive examples of mixing effects through interactions between species, especially for specialist pests (Castagneyrol et al. 2014) and also for drought stress (Grossiord 2020). Both insurance effects and actual mixing effects can be enhanced by combining functionally different tree species (Messier et al. 2019). In many cases, however, the specific tree species combinations that offer the most positive interactions still need to be identified (Baeten et al. 2019).

Actively increasing genetic and tree species diversity may also enhance the forests' resistance and resilience to alien pests (Guyot et al. 2015; Seidl et al. 2018). However, maximal resilience might possibly only be achieved in structurally heterogeneous and mixed, genetically diverse forests. Genetic diversity is a crucial aspect for adapting to climate change. Potential genetic adaptation in the face of climatic variations is favoured by the diversification of species (Vellend and Geber 2005). Other studies confirm that through Close-to-Nature forestry the genetic diversity of the stand can even be improved (e.g. Westergren et al. 2015). To improve the adaptive capacity of forests, Spathelf et al. (2015) suggest enhancing the concept of Close-to-Nature forestry by introducing non-invasive tree species from other climates, and including stress-tolerant, often light-demanding pioneer species (Bolte et al. 2009). Functionally rare tree species, e.g. drought-tolerant and shade-intolerant species, may also enhance the adaptive capacity of the forests (Aquilué et al. 2021). However, non-native tree species have to be selected with care. Ennos et al. (2019) suggest a rigorous testing programme for non-native tree species, which shows attributes facilitating more natural silvicultural systems. Nonetheless, there are a number of non-native tree species which have been used throughout Europe over the last 100 to 150 years. Local experiences with these should be included in the decision-making.

Avoidance of intensive management operations

To develop structurally diverse forests from uniform, even-aged stands, optimization (Messerer et al. 2020) and assessment studies (Knoke and Plusczyk 2001) suggest starting the establishment of young cohorts early, thus avoiding age-dependent risks. This avoids the accumulation of high standing timber volumes and associated risky stand structures, as lower stocking density may increase the vitality of the remaining trees (Sohn et al. 2016). While changing growing conditions might enhance site capacities to carry more trees than in the past (Kubiske et al. 2018), higher stocking densities and standing timber volumes will elevate the risks of storm, drought or insect damage (Hahn et al. 2014). After a high severity disturbance, avoiding intensive operations by leaving a part of the trees unsalvaged may save money (Knoke et al. 2021a) and enhance biodiversity. Avoiding intensive site preparation may on the one hand enhance the establishment of tree regeneration, where other woody plants and ground vegetation facilitate this process, for example through sheltering from direct sunlight and and transpiration (Gomez-Aparico et al. 2004). On the other hand, intensive competition from ground vegetation may also hinder the establishment and hence also the migration of tree species along climatic gradients (Choler et al. 2001).

Supporting landscape heterogeneity and functioning

In naturally dynamic forest landscapes there are complex interactions between probabilistic (such as mean intervals of fire disturbance at different site types favoured by different tree species) and random events (such as where and when a disturbance actually occurs), which affects the successional development from shade-intolerant tree species to shade-tolerant ones. This situation is characteristic for boreal forest landscapes where biodiversity conservation is largely a matter of maintaining a landscape level age distribution which contains sufficient amounts of all age classes ranging from recently disturbed to old-growth (Angelstam 1998; Berglund and Kuuluvainen 2021). In temperate and Mediterranean forests there is currently a higher heterogeneity but, due to intensive past management, there is a need to preserve or favour in managed forests structural elements that enhance the old-growth features present in mature stands (Albrich et al. 2021; Motta et al. 2015).

Figure 5 provides a qualitative attempt to compare the ability of the seven Closer-to-Nature Forest Management principles to contribute to forest resistance, resilience and adaptive capacity. All principles

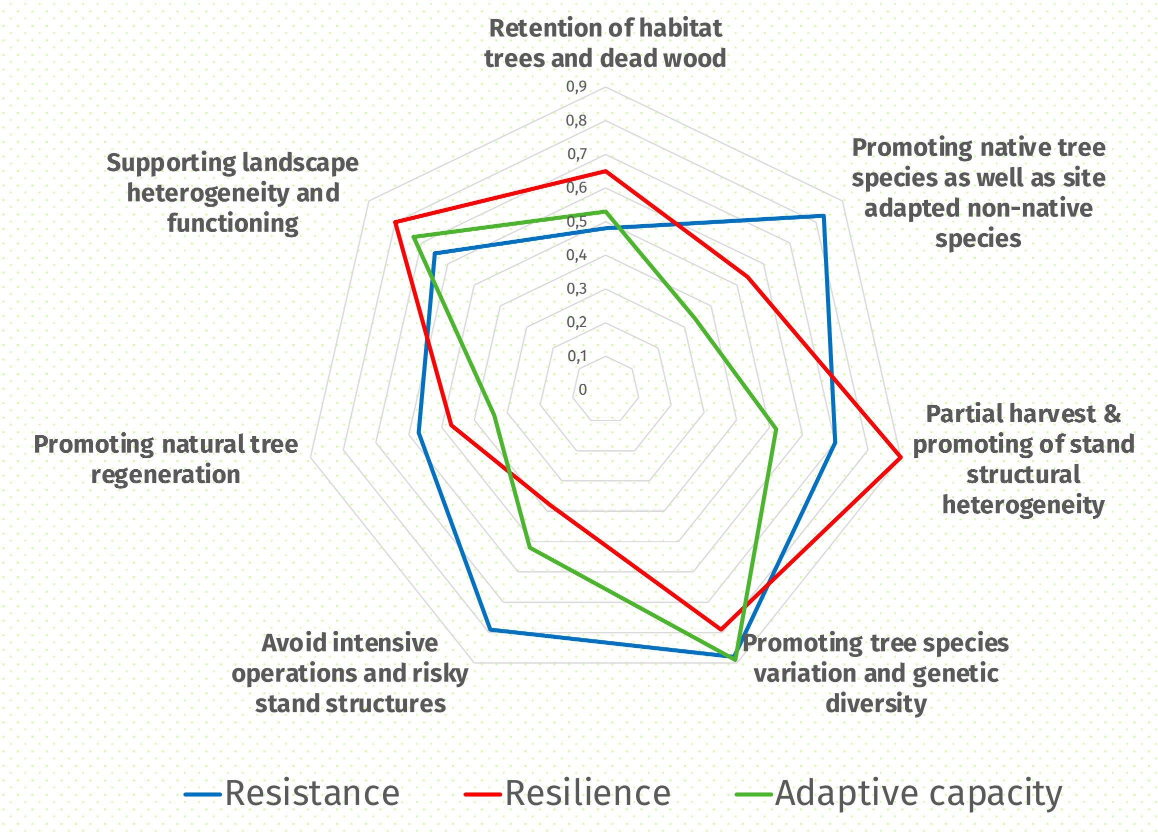

Figure 5. Visualization of the possible impact of principles of Closer-to-Nature forestry on the resistance, resilience and adaptive capacity concerning ecosystem service provisioning (resistance comprises the ability of an ecosystem to resist external stress; resilience comprises correspondingly the ability, when changed due to a disturbance agent, to return to its former dynamic state; adaptive capacity relates to global change, including climate change).

contribute to a certain extent; however, none is able to fulfill all three dimensions to 100%, indicating that combinations of different principles will always be needed, adjusted to the current context and possible future conditions. For all situations where the future conditions are very uncertain, supporting the adaptive capacity has high priority. This means the opportunity to change the composition and management of a forest, should unforeseen future conditions unfold.

It shows that 'Promoting tree species variation and genetic diversity' is of utmost importance in the light of an unknown future. However, our comparison may vary for different contexts and thus provides indications for orientation. For example, the principle 'Promoting natural tree regeneration' had the highest variation among the expert opinions, indicating that its potential would much depend on the context. In regions with more or less stable conditions it may contribute strongly to forest resistance and resilience, while under uncertain or highly changing future conditions its contribution could be lower.

In general, there is a good compliance between management options supporting biodiversity and those promoting forest health, resilience and adaptability. There is, however, one area which needs more attention: the use of native species and local provenances. From a classical conservation point of view the use of local 'genes' is the best way to conserve genes *in situ* and since these genes have been exposed to local conditions including disturbances they are supposed to be well adapted. However, climatic factors are already affecting European forests leading to changes both in tree species composition and in other taxa, indicating a limited ability of local tree species to adapt to climatic changes and consequently to support other taxa.

Hence, forest ecosystem protection must be viewed in a more dynamic way at stand to landscape scales.

This implies that Closer-to-Nature Forest Management should incorporate a range of management measures to support landscape connectivity through green infrastructure (European Commission 2013). This supports natural gene flow to assisted migration to enhance resilience by supporting migration of genes and species across landscapes and regions (Davis et al. 2011; Pretzsch et al. 2013; Hulvey et al. 2013; Radeloff et al. 2015; Cavers and Cottrell, 2015). This means that we cannot enhance resistance, resilience and adaptive capacity of forests if we ignore the rest of the landscape.

To improve the composition and configuration of the non-forest landscape parts, we need comprehensive land-use plans which enhance the structural complexity of agricultural landscapes and ensure improved functional connectivity of representative forest environments (e.g. light-demanding vs. shade-tolerant tree species). Conservation of natural forest is important, for example, in boreal forest areas, as part of a functional green infrastructure consisting of spatiotemporally connected habitat networks (Svensson et al. 2018; Angelstam et al. 2020). Riparian forests are of particular importance to facilitate landscape connectivity (de la Fuente et al. 2018). According to the European Commission, we need a strategically planned network of natural and semi-natural areas, in which we could embed forests combined with a matrix of semi-natural ecosystems. Such strategic plans should also include urban trees, parks and forestry.

5. Closer-to-Nature guidelines – a framework for flexible European-wide implementation

In the previous sections, we have drafted a working definition of a Closer-to-Nature Forest Management vision, which encompasses a variety of nature-based forest management approaches. The vision incorporates important processes and characteristics found in natural forests and aims to increase the resistance and resilience of European forests to current and future anthropogenic pressures. Realizing this vision through sensitive and informed forest management will provide a framework for the further development of multifunctional forests and woodlands across Europe. The following points are key features of this framework:

I. In contrast to the limited habitats found in simple even-aged single species forests, forests managed by Closer-to-Nature Forest Management will feature a diversity of tree species and structures, a variety of tree sizes and development stages, and a range of habitats. Timber harvesting will pay as much attention to what is retained in the forest as to what is removed.

II. Delivery of the Closer-to-Nature Forest Management vision will improve biodiversity and enhance the resistance and resilience of forested and wooded landscapes, and will ensure the continued supply of a wide range of ecosystem services, supporting both rural economies and the wellbeing and welfare of society.

III. The management approaches used to implement Closer-to-Nature Forest Management will reflect regional, ecological, economic, social and cultural variations across the continent. For example, these will include natural disturbance-based forest management primarily in the boreal zone, and continuous cover forestry in many regions in western and central Europe. The approaches will also include, where appropriate and sustainable, the continuation of historically and culturally significant forest management and land-use methods such as coppice systems and wood pasture that have created distinctive landscapes rich in biocultural diversity and cultural heritage.

The most important principle is that expanding the use of Closer-to-Nature Forest Management will mean employing a variety of silvicultural methods to develop multifunctional forests that: reflect local climates and forest and site types; can sustain biodiversity and facilitate adaptation; provide the desired range of ecosystem services. Managers should embrace diversity, learn from natural processes that influence their forests, anticipate the impacts of climate change, and plan to develop forest ecosystems that can be sustained through an era of profound uncertainty. This should be done in consultation with stakeholders and it will take appreciable time for the effects of adopting this approach to become apparent – adaptive learning will be needed for success.

Successful adoption of Closer-to-Nature Forest Management in European forests and woodlands will require a systematic approach based on well-established principles of active adaptive management. Participation and social learning should be included to secure diversity of management and decentralized decision making. This will involve:

- regularly gathering information about the forest ecosystems in a particular area
- analyzing their present condition and potential risks to their ability to deliver key ecosystem services
- formulating with stakeholders a shared long-term vision of the future structure and composition of these forests and woodlands
- developing a forest management plan to support that vision which implements the principles of Closer-to-Nature Forest Management
- using defined indicators to monitor the response of the forests to management interventions and adjusting further interventions accordingly.

Introducing this management approach will not achieve success overnight and there will be a need for silvicultural flexibility that reflects the continuing and uncertain impacts of climate change.

Checklist/guidelines for the implementation of Closer-to-Nature Forest Management

A structured decision-making framework underpinned by a long-term forest management plan will be essential in guiding the transformation process. We outline below a checklist to help those seeking to introduce this approach into European forests. The checklist is in order of actions to be taken and the actions are grouped according to the stages in the adaptive management cycle.

DEVELOP PLAN

a. Define the area of interest where Closer-to-Nature Forest Management is to be applied. This could be a country, a region, an area of defined landscape character, a specific forest type within a region or forest, or an individual forest enterprise.
b. Develop a long-term vision (i.e. up to the end of the century) quantifying the future structure and species composition of the forest and woodland resource and the spatial distribution of the different components (forest landscape plan). Then test the vision through the following planning stages.
c. Support forest managers/owners to help them engage with stakeholders to explain the thinking behind the proposed introduction of Closer-to-Nature Forest Management and ensure that they involve them throughout the process. This could include creating a steering or other advisory group, and making use of existing networks in the area/region to support the dissemination of Closer-to-Nature Forest Management (see Annex 1).
d. Assemble existing knowledge about the forest as a social-ecological system (e.g. portfolios of goods, services and values, current and anticipated demand for various ecosystem services, socio-economic benefits, tree species, age-class distribution, the presence of any special habitats, key functions, presence and density of browsing animals, recreation and amenity value, relevant cultural landscapes etc.).
e. Identify and remedy gaps in the knowledge base (e.g. which silvicultural systems are being used, site types present in forests, presence of rare fauna/flora etc.). Use experts where necessary to carry out surveys.
f. Assess the natural and anthropogenic disturbance regimes (e.g. wind, fire, fungal and insect pests, traditional management etc.) that are and may have been important. Consider their predicted frequency of occurrence in the future (i.e. under climate change) and the potential impact on forest structure and dynamics.
g. Determine to what extent natural site conditions have been changed in the past through management (e.g. drainage) and evaluate options for habitat restoration.
h. Evaluate the likely sensitivity of the main tree species and forest structures present to anticipated climate change, including the extent to which vulnerability can be modified by silviculture.
i. Identify tree species combinations (e.g. use Forest Development Types, Larsen and Nielsen 2007) that are likely to be best adapted to future conditions. Such combinations can include non-native species if these are site-adapted and carefully screened.
j. Evaluate the capability of the vision (see b) to maintain and/or enhance biodiversity, secure forest health and improve adaptation to global change and deliver other key forest ecosystem services. Make adjustments to the vision as necessary to limit negative trade-offs and finalize.
k. Formulate the agreed vision in a long-term forest management plan which sets out the range of measures to be taken to realize the aspirations of Closer-to-Nature Forest Management.

IMPLEMENT PLAN

l. Using local knowledge and existing good practice examples (see Annex 1), select the forest management approach that will be most appropriate for delivering the long-term vision. Identify silvicultural methods which should support biological and biocultural diversity, forest health/stability and robustness to global change (e.g. tree species richness/diversity, natural regeneration, structural heterogeneity at the stand and landscape level, etc.) while continuing to provide sustainable timber supplies.

m. Identify the priority areas for silvicultural intervention in the short- and medium-term. Ideally, these should be actions that provide rapid benefit to the forest ecosystem, the forest enterprise and wider society.

n. Consider the critical skills required to implement the plan (e.g. skilled forestry professionals and workers, wildlife managers, etc.) and see whether these are available; if not, invest in training.

o. See if there is a need to invest in infrastructure (e.g. improved access roads for harvesting) or to remove inappropriate elements (e.g. drainage systems, roads near a primary forest reserve).

p. Consider if there are other constraints to implementing Closer-to-Nature Forest Management (e.g. browsing pressure caused by high ungulate populations resulting in regeneration failure) and seek a shared resolution of the issue.

MONITOR ACTIONS

q. Determine what will be the key indicators of ecosystem response to Closer-to-Nature Forest Management (e.g. species, water quality, timber productivity, carbon sequestration, amount of dead wood and other special habitats). Selection of indicators should take account of local conditions; they should be tractable and be capable of providing measures of the success (or otherwise) of management interventions.

r. Develop quantitative guidelines for these indicators as far as is possible (e.g. how many habitat trees to retain and the desired amounts of different categories of dead wood).

s. Establish a cost-effective monitoring system that will provide robust information on these indicators over time. Ensure that such information is properly archived for future reference.

t. Carry out baseline surveys of the key indicators to provide information to assess the future response of the forest to management intervention.

EVALUATE OUTCOMES

u. Make use of existing networks and reference forests to inform the evaluation of the outcomes of management actions. If there are no sites or information relevant to a given location or forest type, then consider establishing operational trials of the approach which should be of a sufficient scale and duration to provide information about the impacts upon key indicators. This may require collaboration with other stakeholders.

v. Review progress by reviewing the management plan at regular intervals (i.e. at least once every 10 years).

ADJUST

w. Use the monitoring information for guidance and adjust the management plan and silvicultural measures as appropriate.

Formulating a long-term vision and the need for patience

Experience in different parts of Europe shows that the transformation of forests from even-aged management to irregular structures can take decades (e.g. Kerr et al. 2010; Schütz et al. 2012). Therefore, it is essential that managers determine a long-term vision for implementing Closer-to-Nature Forest Management in their forests. This vision should attempt to quantify key habitat features to be achieved over time including future species composition and the distribution of different forest development stages. This process needs to take account of the potential impacts of climate change and identify measures that will increase forest resilience to these impacts. Generalized statements (e.g. 'we aim to restore natural woodland structures') should be avoided since they provide no detail to allow future managers to evaluate the success or failure of measures taken to support Closer-to-Nature Forest Management.

The vision should be formulated in a forest management plan that is revised at 10–20-year intervals and the revision informed by a carefully selected set of forest and biodiversity indicators which can be cost-effectively monitored at regular intervals over decades to assess progress against targets. The preparation and implementation of such plans should be aided, as and where appropriate, through long-term financial support mechanisms to ensure that Closer-to-Nature Forest Management is available to all sizes and categories of forest owners and enterprises. Wherever possible, the incentives should be designed to stimulate a 'small and often' approach to management interventions, so that forest managers are regularly learning from the impact of their actions. Because of the length of time that may be required to see how forests respond to interventions, it is important that managers are both patient and flexible in designing and implementing silvicultural prescriptions.

Dissemination of Closer-to-Nature Forest Management across spatial scales

Successful resolution of the information and communication gap between science and application is often based on a combination of evidence-based and experience-based information sources (Pullin and Knight 2005; Fabian et al. 2019). In the case of dissemination of novel management concepts for systems with long turnover rates such as forests, a central difficulty is the long time needed for testing, application and evaluation. This is even more important as adaptation of ongoing management is a decision with long-lasting consequences for the forest itself and across levels of governance, and iterative adjustment of management decisions is a lengthy process. Additionally, desired portfolios of benefits from forests are dynamic over time and space. Hence, identifying existing examples and learning from experience is most effective when combining evidence and experience (Fabian et al. 2019). However, this is not trivial as the biophysical and socio-economic conditions of forest management are highly region-specific, in contrast e.g. to more technical systems that can be applied in other contexts often only with slight adaptation.

Convincing good practice examples of forest management for particular outcomes (e.g. Puettmann et al. 2012; Krumm et al. 2020) are ideally based on long-term experience and continuity over years and even generations. Their value for science and application depends on the clearness of the concepts applied, and on the quality of their documentation allowing dissemination and replication. Wherever possible, the documentation should provide information on the financial and operational implications of introducing Closer-to-Nature

Forest Management so that the cost-effectiveness of the approach can be evaluated. Such data-based management examples provide the basis for modelling approaches, and are crucial for generalization, upscaling and transformation of concepts and experience to other contexts. They also permit the evaluation of applied measures, and visualization and demonstration as part of dissemination (e.g. Pretzsch 2009).

Another fundamental issue is the spatial scale and extent of management decisions affecting biodiversity as they might focus on the single tree level up to the stand, the enterprise, entire forest and woodland landscapes. Thus the functionality of forest habitat networks must even extend to the regional level (i.e. green infrastructure; Angelstam et al. 2020). Hence, dissemination of Closer-to-Nature Forest Management applied at multiple scales needs to consider well documented and data-based good practice examples on every spatial scale. This can become extremely demanding as the size of the area increases since best practice examples are often not available. A diversity of different forest management approaches has been developed reflecting the varied socio-ecological realities across the European continent. This includes different approaches aiming at nature-based forest management on an enterprise and landscape level, long-term silvicultural trials on the stand level as well as demonstration and training sites at the plot level (see Annex 1).

Additionally, reliable networks are needed and should be supported to allow forest owners, forest managers, experts in biodiversity conservation, spatial and territorial planners, researchers and policy makers to discuss jointly the benefits, but also the costs of Closer-to-Nature Forest Management with consequences for education, training and lastly for policy development (see Annex 1).

6. Barriers and enablers for the implementation of Closer-to-Nature Forest Management in Europe

The interest in alternative, integrative forms of forest management has grown in many parts of the world, including Europe (Puettmann et al. 2015; Krumm et al. 2020). This interest has been motivated by the recognition of many problems associated with conventional, intensive forms of forest management that are focused on production of timber and woody biomass and fail to achieve a balanced provision of other desired ecosystem services. These problems include possible negative influences on biodiversity and habitat quality (e.g. Paillet et al. 2010; Bauhus et al. 2017b), on soils and carbon and nutrient cycling, on provision of freshwater (e.g. Swank et al. 2001; Clarke et al. 2021) and on recreational opportunities and aesthetic perceptions of forests (e.g. Font and Tribe 2000; Ribe 2005).

Alternative approaches to forest management such as Closer-to-Nature Forest Management that aim to provide structurally and compositionally diverse forests can mitigate many of the above effects. They may also support higher levels of multiple ecosystem service provision (Pukkala 2016; van der Plas et al. 2016; Lafond et al. 2017; and other sections in this report) and facilitate the adaptation of forests to climate change in many ways (Section 4).

Although many potential benefits are increasingly underpinned by scientific evidence, the uptake of Close-to-Nature forest principles in forests managed for wood production is still slow in Europe and elsewhere (Schütz et al. 2012; Puettmann et al. 2015). This begs the question, which factors pose impediments to the uptake and implementation of such forms of forest management including Closer-to-Nature Forest Management (see definition section 1) and which factors enable it?

Retention of habitat trees and dead wood

The retention of forest structures during timber harvesting (leaving biodiversity-promoting structures after harvesting) including promoting minority tree species and rare habitats has evolved as a central concept of ecologically sustainable forest management in support of biodiversity and ecosystem functioning and has also been incorporated into Closer-to-Nature Forest Management (e.g. Gustafsson et al. 2012, 2020; Section 3 and 4). The concept is supported and demanded by nature conservation legislation, for example the European Flora-Fauna-Habitat and Bird Protection guidelines, to ensure that conditions of populations of listed species do not deteriorate in managed forests. It has also been adopted in certification schemes of sustainable forest management (e.g. FSC, PEFC).

For forest owners, there are obvious economic impediments since the provision of habitat trees can only be achieved through proportional reductions in harvesting. In addition, retention measures may restrict future stand access and forest operations. Where these measures are not regulated by legislation, their practical application by private forest owners may be limited by inadequate financial incentives for their implementation and a lack of accompanying measures. Thus, the application of this principle could be promoted by better rewarding private forest owners for these habitat conservation services.

Promoting native tree species as well as site-adapted non-native species

Trees are the foundation species of forest ecosystems with special importance for the structure of a community by creating and determining the living conditions for many other organism groups that have co-evolved with them. Hence, they are very important for native biodiversity, and this is reflected in nature conservation legislation (e.g. native forest communities form the backbone of the forested Natura 2000 reserves). Nevertheless, we will increasingly face situations where native tree species are already at high risk or will be in the foreseeable future, and so need to be replaced - at least partially - by better adapted tree species and provenances. The least impact on biodiversity would occur where they are replaced by other native species including previously rare ones. However, the knowledge base for some rare native species is still very small.

Non-native tree species could be used that support a large proportion of the dependent biodiversity due to their close relationship to native species (e.g. Vogel et al. 2021). Where non-native species are cultivated, it would be important to ensure that their proportion in stands and landscapes does not impact the viability of populations of forest-dwelling species. For example, desired proportions of native species could be ensured through minimum standards in subsidy schemes or forest certification or in management plans of Natura 2000 reserves.

Promotion of natural tree regeneration

Adoption of this principle is largely motivated by cost savings when compared to planting (e.g. Tahvonen et al. 2010), by less root damage and higher initial seedling densities which may increase genetic diversity and reduce risks against some herbivorous insects (e.g. pine weevil *Hylobius abietis*). Since natural regeneration consists typically of many more juvenile plants than would be conventionally planted, it is subject to a higher degree of natural selection and hence promotes the adaptation of tree populations to changing site conditions. It may benefit also from epigenetic processes, where offspring from mother trees that were under stress during seed formation show higher resistance to these stress factors such as drought (Amaral et al. 2020; Bose et al. 2020). If natural regeneration develops as early (advance) regeneration, it also increases the resilience of forest stands in the case of windthrow or insect damage to mature trees. It works best where competitive understory vegetation is sparse while in other environments the vegetation may work as a facilitator. Protecting seed dispersing animals or improving their habitat conditions may also facilitate natural regeneration processes, in particular of large-fruited tree species (e.g. jays and acorns).

However, natural regeneration can be severely hindered or even made impossible by high populations of browsing ungulates (e.g. Motta 1996). In addition, it may not be the best option where the population of parent trees is not adapted to future climatic and site conditions, or if other desirable species do not regenerate in sufficient numbers. In these cases, active adaptation through complementary artificial regeneration (planting) is likely to be necessary. The use of natural regeneration is sometimes discouraged because it does not receive the same incentives or subsidies as planting, or because reforestation laws do not allow sufficient time for natural regeneration to reach the required stocking standards.

Partial harvests and promotion of stand structural heterogeneity

This principle has in part developed from the management of naturally uneven-aged forests with tree species that do not cope well with large canopy openings, and also from selection felling of large-dimension, valuable trees (section 2). The resulting forests are typically characterised by relatively high levels of growing stock. In addition, they are considered to be more resistant and resilient in relation to several types of disturbances. Hence, policies aiming at ecosystem-based climate change mitigation would support this principle. In many parts of Europe, the avoidance of clear-felling also receives support from the public and nature conservation organisations.

At the same time, growing large trees may increase the vulnerability of forests to drought, windthrow and related secondary disturbances (Grote et al. 2016). Small canopy openings limit the establishment of more light-demanding, and drought-adapted tree species such as oaks (Kohler et al. 2020). Therefore, larger gaps may be needed where the current composition of shade-tolerant species is not suitable for future climatic conditions.

Many other factors can make the application of selection systems and other forms of partial harvesting challenging (Puettmann et al. 2015). These include the need for highly trained workers and specialized low-impact machinery, health and safety considerations, increased planning, operation and monitoring costs, investments and maintenance of a dense road infrastructure, or the inevitable harvesting damage to residual trees. Where these additional costs are not outweighed by the benefits of higher income, greater flexibility or reduced economic risks when compared to conventional approaches (e.g. Hanewinkel et al. 2014; Knoke and Wurm 2006), other incentives may be required. In those parts of Europe such as the boreal north where there is a lack of tradition in selection systems and partial harvesting practices, substantial investments in research, education and training would also be required to implement these practices.

Promoting tree species variation and genetic diversity

Tree species richness is one of the most important factors for the diversity of forest dwelling organisms in European forests (Ampoorter et al. 2020). Tree species and genetic diversity are also central forest properties in support of resistance, resilience and adaptive capacity in relation to climate change (section 4; Larsen 1995, Bauhus et al. 2017a) and thus are promoted by policies to adapt forest management. Major impediments to establishing and managing more diverse forests are related to the higher management complexity of tree species mixtures and the related increased costs (Puettmann et al. 2015), high populations of browsing ungulates and with regards to genetics, the legislation in some jurisdictions that prevents the import and mixing of provenances.

Avoidance of intensive management operations

Intensive forest operations include large clear cuts without retention, removal of harvesting residues, site and soil cultivation and use of pesticides, herbicides and mineral fertilizers. They typically aim for a high harvesting efficiency, increasing the productivity and uniformity of tree crops and reducing the establishment risks of artificial regeneration. Avoiding such intensive operations including temporal or spatial restrictions on management and remediation and creation of biotopes (e.g. Scherzinger 1996) has mostly economic impediments. There may be situations, due to the presence of very competitive vegetation (e.g. invasive species or ongoing eutrophication) where the establishment of trees may not be possible without intensive operations. Avoiding intensive operations limits negative impacts on biodiversity, can reduce carbon emissions from soils and off-site effects on water bodies, and may reduce soil compaction caused by heavy harvesting machines. In many European regions, less so in the boreal north, limiting such operations is widely supported by public opinion and facilitates compliance with environmental protection legislation.

In some situations, the application of these principles of Closer-to-Nature Forest Management would be economically viable if forest owners receive financial incentives for providing ecosystem services.

Supporting landscape heterogeneity and functioning

The management principles of Closer-to-Nature Forest Management lead to an emphasis on stability, productivity, diversity and continuity of forest conditions to integrate multiple forest management goals. In southern and central Europe, this integration is aimed for at small spatial scales, ideally within individual forest stands through maintaining mixed-species and uneven-aged forests. In northern boreal forests the integration occurs at larger scales due to different disturbance regimes and extensive even-aged stands (Bauhus et al. 2013; Kuuluvainen et al. 2021). Whereas an emphasis on managing forests at small spatial scales may appear to lead to homogenous forest landscapes, the situation in Europe today is quite variable, due in part to the diversity in land ownership and management histories. However, in many jurisdictions, there are no or only few established tools and approaches in place for landscape-level forest planning and management across forest ownerships. Nevertheless, there are some large forest companies (for example in Sweden) or state forest companies that do carry out landscape-scale planning and management (Bergman and Gustafsson 2020).

Some existing landscape-level instruments have been developed that aim to conserve biodiversity in reserves such as Natura 2000 that span different properties, or to manage water catchments. However, these are typically oriented towards individual objectives or restrictions but do not consider the whole suite of management objectives and their synergies and trade-offs at the landscape level. The highly fragmented forest landscapes and frequently small-sized forest properties found in many parts of Europe (Pulla et al. 2013) pose serious challenges to landscape-level planning and management approaches. A key challenge is to conserve, manage and restore sufficient areas as functional habitat networks. This is captured by the term green infrastructure i.e. "a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings" (European Commission 2013).

One important aspect of landscape functioning to support biodiversity is the patterns and structures created by natural disturbances such as windthrow, fire or bark beetle outbreaks. While historically several principles of Closer-to-Nature Forest Management aimed to reduce the occurrence of natural disturbances and associated damage to stands, it has been recognized that the practices may also reduce landscape-level biodiversity (e.g. Schall et al. 2018). In addition, managing the risks of fires, pests, pathogens or invasive species also requires coordinated efforts at the landscape level. To address this issue, different forms of collaborative or community forest management, which exist traditionally in many European regions (Jeanrenaud 2021), could be further promoted. This may require financial incentives to establish the organisations and develop their forest management capacities as well as supporting the acquisition of data and use of landscape planning tools.

Missing information and issues to consider

The number of points included in the checklist in section 5 reveals the magnitude of the changes required to successfully implement Closer-to-Nature Forest Management across Europe. Scientific and practical understanding of aspects relevant to this change process is increasing, and inevitably further work will reveal the need to make adjustments and/or additions to the checklist.

Gaps in the knowledge base

Although National Forest Inventories (NFIs) provide excellent summary information on the state of forests across Europe including details of their age class distribution, growth rates, and species composition, they provide limited or no details of the way forests are managed (e.g. silvicultural systems that are used) or whether the harvesting protocols or patterns of mortality due to disturbances conform to the assumptions built into predictions of forest development over time (Mason et al. 2021; Schelhaas et al. 2018). This deficiency tends to be most acute for private forests which comprise about 60% of European forests with nearly 16 million forest owners and whose perspectives have been comparatively little studied, especially for small scale owners (Tiebel et al. 2021). Thus, although the desirability of management plans for private forests is widely promoted (Forest Europe 2020), the information contained in such plans seems often to be poorly collated.

Species sensitivity and Forest Development Types

In many parts of Europe, the impacts of climate change and associated hazards (e.g. bark beetle attacks after severe drought) are likely to force the re-evaluation of a forest economy dominated by one or two species, which have often been planted off-site or introduced from other parts of the world (see section 4). Creating mixed stands of irregular structure is one of the preferred ways of adapting forests to climate change but this can be challenging, in part because of a lack of specific silvicultural guidelines for creating and managing mixed stands and the increased management complexity that comes with mixtures (Bauhus et al. 2017c; Pretzsch and Zenner 2017).

One solution is to make greater use of dynamic Forest Development Types (FDTs) where, in a given location, a long-term goal is defined for forest development and species composition taking into account current and predicted climate and soil conditions (Larsen and Nielsen 2007). The increasing availability of decision support systems that integrate the present and future features of a site with knowledge of individual tree species' eco-physiological requirements can help managers to identify species combinations that will provide enhanced resilience to future conditions (Mason et al. 2018). An FDT framework can also provide a structured approach to guide the introduction of non-native species that seem less sensitive to climatic hazards (e.g. Douglas fir compared to Norway spruce in southern Germany, Vitali et al. 2017).

Site classification

Another area where important information is often lacking is on site factors including soil properties. This knowledge is essential to support accurate choice of tree species adapted to future climates and can also influence the success of attempts to diversify single species forests. Information on soils and site-specific precipitation and energy balance is also needed for local model-based predictions of soil water availability under different climate change scenarios. Detailed soil information is also needed to guide silvicultural and harvesting practices and thus avoid soil damage. Good information on the soils found in a forest should be a precondition for wider use of Closer-to-Nature Forest management.

The role of markets

In light of the increasing global change pressures on our forests, one could argue that the role of markets would become less and less important, because the main challenge would be to retain or create ecologically functioning forest ecosystems and landscapes. However, a substantial part of European forests is in private ownership, where economic trade-offs caused by ecologically desirable forest management strategies are relevant. While the long-term economic performance of some Closer-to-Nature Forest systems is quite competitive (Tahvonen et al. 2010), the application or adoption of many of the above principles such as “Retention of habitat trees” may cause opportunity costs for forest owners. Currently, the potentially higher provisioning of ecosystem services when compared to conventional forestry is not financially compensated or rewarded through market mechanisms. Yet, their application may in many instances make management more complex, when compared to conventional forest management. In some situations, the application of these principles of Closer-to-Nature Forest Management would be economically viable if forest owners receive financial incentives for providing ecosystem services. Because applying Closer-to-Nature Forest Management principles will supply public goods (e.g. biodiversity conservation or climate regulation) at higher levels than conventional forestry (Knoke et al. 2020), financial rewards of perhaps certified Closer-to-Nature Forest systems could be a game-changer. These rewards could, for example, be implemented via a price premium for timber produced under Closer-to-Nature Forest Management or through a fair conservation premium for providing habitat. Fair conservation payments would consider the market-based assessment of forest owners’ true opportunity costs and include producer surplus as a premium. Conservation auctions could help achieve this (Bingham et al. 2021; Müller et al. 2020).

7. Conclusions and the way forward

This study shows how the adoption of a Closer-to-Nature Forest Management approach can underpin the establishment of new thresholds for sustainable forest management in the EU Forest Strategy for 2030 and so further support the multifunctional management of European forests.

Greater use of Closer-to-Nature Forest Management principles would substantially contribute to biodiversity restoration and preservation in managed forests across Europe. It would also contribute to improved resistance and resilience and thereby to an increased capability of forests to adapt to present and future climate changes and other global threats.

Different approaches may be used in different regions of Europe, reflecting the variation in forest types, in the intensity and scale of disturbance regimes, and in the ways forests have been used in the past and will be managed in the future. However, **the general principles of Closer-to-Nature Forest Management should be similar across all regions:**

- learning from and permitting natural processes
- embracing the heterogeneity and complexity of forest structures and patterns
- integrating forest functions at small spatial scales
- using a variety of silvicultural systems based on knowledge of natural disturbance patterns of the region
- low-impact timber harvesting with equal attention being paid to what is retained in the forest as what is removed, thereby preserving habitats, forest soil and microclimate.

The management of uneven-aged and irregular forests has a long tradition in Europe with examples present in all European biomes, and this approach can be considered as a viable alternative to even-aged stands managed through clear-cutting. Since almost one-third of European forests are uneven-aged, there are many **opportunities to learn from existing practices**. Because the wider adoption of Closer-to-Nature Forest Management will require a substantial effort in knowledge transfer, it is very important to **consolidate existing networks of trials and demonstrations relevant to this process**. Ensuring the long-term continuity of such 'demonstration forests' will be invaluable in the ongoing social learning process and in helping to convince forest managers and other stakeholders of the benefits of this new approach. Ideally, such a knowledge transfer network should cover all major regions and forest types found in Europe. This network could be linked to others seeking to preserve traditional management methods, cultural landscapes and their associated biocultural diversity that is an important European richness recognized both by IUCN and the Natura 2000 network.

Adaptive management should be used as a way to tackle uncertainties, by regularly observing forest response to management interventions, evaluating these responses and adjusting management strategy accordingly. **A similar adaptive approach is urgently required to evaluate the impact of policy measures and support mechanisms** proposed to encourage adoption of Closer-to-Nature Forest Management, since such information will be invaluable for improved policy implementation.

The introduction of Closer-to-Nature Forest Management is not a 'quick-fix' and **policy makers must provide long-term and consistent support measures** to encourage forest managers and other stakeholders to adopt this strategy.

Closer-to-Nature Forest Management has the potential to support biodiversity, adapt forests to climate change and provide ecosystem services to a higher level than conventional forest management. Convincing private owners to follow this approach in support of achieving broader, societal objectives will require **improved knowledge transfer and the creation of schemes that reward private forest owners for providing ecosystem services**. There is an urgent need to review existing subsidy and taxation regimes affecting private forestry, and to consider how these might be changed to further the uptake of Closer-to-Nature Forest Management. Further, there is a need to **develop and use new technologies and tools** (GIS, GPS and remote sensing) to ease management and secure control of these more diverse and structure-rich forests.

There are still some uncertainties about the effect of the diverse elements of Closer-to-Nature Forest Management on biodiversity conservation and ecosystem health, and how they will affect other ecosystem services including wood production under different management conditions throughout Europe. This calls for **more collective learning, experimentation and research**.

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Annex 1: Networks, practice examples and research plots supporting the dissemination of Closer-to-Nature Forest Management

Existing networks

Fabian et al. (2019) found that there was an urgent need for broad and diverse dissemination activities to reduce the gaps between science and practice, and between forestry aimed at wood production and forest biodiversity conservation. Apart from short, audience-targeted and synthesizing publications in national languages and specialized websites, direct personal contact and exchange with professionals was identified as most important. For successful dissemination and adaptation of Closer-to-Nature Forest Management in different forest and woodland types in Europe, networks are needed that create opportunities for stakeholders interested in different aspects of forest ecosystem services to meet and exchange personal views and experience. Important existing and well-established networks for nature-based forest management and conservation planning include: Nordic Forest Research; Pro Silva; the European Integrate Network; Long-term Social-Ecological Research network eLTER; the FUNDIV Europe platform; GENTREE; the Biosphere Reserves; and the forested Natura 2000 sites.

Nordic Forest Research (SNS)[1] is a cooperating body under the Nordic Council of Ministers which "strives to enhance benefits for the Nordic region and contribute to a green, competitive and equal society in the Nordic region". One main aim of SNS is to promote research for sustainable forestry, to advise the Nordic Council of Ministers, and to communicate research results.

The ***non-governmental organisation Pro Silva***[2] aims to promote and further develop Close-to-Nature and continuous cover forest management based on the model of natural forest dynamics including disturbances (Schütz 2011; Schütz et al. 2016; Mason et al. 2021). It consists of independent national member organisations from 31 European countries and six partner organisations from South and North America and Asia. Its main activities include the exchange of experiences, the provision of guidance for Close-to-Nature forest management, policy support, and a network of exemplary forests.

The ***European Integrate Network***[3] focuses on 'integrated forest management' combining segregated with integrative management approaches for the sustainable provision of several ecosystem services, including biodiversity, in a forest landscape. Meanwhile, 19 member countries take part voluntarily with representatives from forest and nature conservation policy and practice, with the European Commission being an observer. This network encourages exchange through joint scientific publications (Krumm et al. 2020; Blicharska et al. 2020) and policy briefs (Winkel et al. 2020), the organisation of workshops, field training and excursions to good practice examples and demonstration sites, so-called marteloscopes.

The mission of ***eLTER***[4] is to facilitate high impact research and provide new insights about the compounded impacts of climate change, biodiversity loss, soil degradation, pollution and unsustainable resource use on an ecosystem level. The pan-European in-situ research infrastructure serves multiple scientific communities. At socio-ecological eLTSER Platforms, a socio-ecological approach is used to study integrated human-nature systems, and to integrate stakeholder knowledge.

The ***FUNDIV***[5] platform supports communication and knowledge exchange among stakeholders, scientists, policy makers and the public regarding the understanding about the functional significance of biodiversity in order to provide forest ecosystem services in representative European forest types. The aim of this platform is to understand and quantify how tree species diversity can be used to foster the provision of the most important ecosystem services.

1 https://nordicforestresearch.org/
2 https://www.prosilva.org/
3 https://integratenetwork.org/
4 https://elter-ri.eu/
5 http://project.fundiveurope.eu/

GENTREE[6] aims to provide the European forestry sector with better knowledge, methods and tools for optimising the management and sustainable use of forest genetic resources in the European context.

Biosphere reserves[7] are 'learning places for sustainable development'. They are sites for testing interdisciplinary approaches to understanding and managing changes and interactions between social and ecological systems, including conflict prevention and management of biodiversity. They are places that provide local solutions to global challenges. Each site promotes solutions reconciling the conservation of biodiversity with its sustainable use.

Natura 2000[8] is far more than the world's largest network of protected areas, as it does not exclude economic activities as long as they are compatible with safeguarding and actually maintaining biodiversity. Natura 2000 has 26,000 protected sites, of which 49% are forested, corresponding to 21% of the entire forest area in the EU, and can be seen as the umbrella network for nature protection in forests and targeted but region-specific Closer-to-Nature Forest Management approaches.

The LIFE project GoProFor[9] has initialised a database for good practice examples. Partly included are many **regional and national networks** of protected but managed forest areas (e.g. Bücking et al. 2000), such as for example the French Réserves Naturelles[10], the Swiss Sonderwaldreservate[11], the Schonwälder in Baden-Württemberg (Germany)[12], the Native Pinewoods of northern Scotland (e.g. Summers 2018), and the "Ekopark" concept of the Swedish state forests (Jonsson et al. 2019; Bergman and Gustafsson 2020), which allow targeted management to safeguard rare habitats and endangered species.

These and the following examples, which are far from complete, illustrate the wide range of networks differing in their objectives, spatial scale and duration. Successful dissemination of Closer-to-Nature Forest Management must profit from these existing networks and regional expertise and use them as **platforms for learning through evaluation** (e.g. Angelstam et al. 2019), thus further developing the concept of Closer-to-Nature Forest Management together with actors across the sectors.

Good practice examples of Closer-to-Nature Forest Management at enterprise and landscape level

The ***Pro Silva exemplary forests*** demonstrate exemplary and successful long-term application of Close-to-Nature practices developed in different European contexts, and this network is being extended to Mediterranean and Eastern European regions. The purpose is (1) to attract partners for on-the-ground demonstration of Close-to-Nature forest management principles, (2) to actively promote exemplary forests for education, and (3) to analyse and document the development of complex forest structures and management success. Each example forest is documented e.g. by important site and stand characteristics, forest history, forest functions, and technical and economic framework conditions.

The European Integrate Network has created a set of 32 ***good practice examples***, including forest enterprises, forest owners and regional initiatives from a local to the landscape level across Europe. They demonstrate how biodiversity can be promoted and combined with management for other demanded ecosystem services such as wood production, protection against natural hazards and recreation (Krumm et al. 2020). Selected enterprises demonstrate how traditional forest management with focus on timber production can be preserved to a certain level and further developed to support biodiversity conservation. It is obvious that acceptance of regional cultural differences is crucial in order to maintain local value chains and at the same time to promote biodiversity conservation.

Strict forest reserves must be seen as a core element of any integrated forest management concept (Motta 2002; Frank et al. 2007; Nagel et al. 2013; Krumm et al. 2020). They include the last remnants of unmanaged

6 https://www.gentree-h2020.eu/
7 https://en.unesco.org/biosphere/
8 https://ec.europa.eu/environment/basics/natural-capital/natura2000/index_en.htm
9 https://www.lifegoprofor-gp.eu
10 https://www.reserves-naturelles.org/
11 https://www.bafu.admin.ch/bafu/de/home/themen/biodiversitaet/fachinformationen/massnahmen-zur-erhaltung-und-foerderung-der-biodiversitaet/oekologische-infrastruktur/waldreservate.html
12 https://www.forstbw.de/schuetzen-bewahren/waldschutzgebiete/schonwaelder/

near-natural forests or formerly managed and now completely protected areas with no human activities at all, so that the forest can develop naturally again (Bücking et al. 2000). They are not only ecologically important as biodiversity hotspots (Jonsson et al. 2019) but are crucial for inspiration and learning for Closer-to-Nature Forest Management (Larsen et al. 2010; Nagel et al. 2012; Schütz et al. 2016) including the study of natural forest dynamics (e.g. Edwards and Mason 2006; Angelstam et al. 2011; Petritan et al. 2015; Peterken and Mountford 2017). Furthermore, they are essential for the re-colonisation of threatened species into managed forests. Hence, they are of utmost importance for mutual learning for experts in nature conservation and forest management and also for the interested broader public (e.g. Mergner and Kraus 2020).

Research plots of Closer-to-Nature Forest Management at stand level

Growth and yield plots are one of the oldest approaches to study the development of trees and forests over long time periods ranging from decades up to more than a century (Pretzsch 2009). Even though they are not designed for biodiversity monitoring, these unique long-term results help to understand the impact of different types of stand management on forest development (Pretzsch 2019) and thus through structural indicators monitor the current status of biodiversity in these stands. A major advantage of growth and yield plots is that they provide an invaluable data source for developing and validating models of stand level responses including aspects of biodiversity to interventions. However, due to their small size (typically < 1.0 ha) an evaluation of management effects on ecosystem services on a larger spatial scale or on landscape aspects is limited. Partly for this reason there has been growing emphasis on the installation of larger scale trials which can allow an in-depth evaluation of irregular silviculture on ecosystem services beyond stand scale (e.g. Alder et al. 2018; Calladine et al. 2015).

The ***network of research stands*** of the Association Futaie Irrégulière (AFI) are regularly monitored to provide detailed growth, economic and ecological data on Closer-to-Nature Forest Management (Susse et al. 2011). These research stands can be around 5-15 ha in size, with 10 permanent plots identified within the stands, where all trees and regeneration are spatially identified and monitored at five-year intervals using standard protocols. This allows the use of remote sensing to monitor tree growth and stand development (Bennett et al. 2020). In 2020, the AFI network consisted of 130 research stands of which two-thirds were in France, and the rest in seven different countries across western Europe[13]. A recent summary report provides an overview of findings from the network (AFI, 2020).

Marteloscopes as training tools at plot level

Marteloscopes are a well-recognized approach in silviculture training to develop forest management skills in specific contexts on the plot level (Bruciamacchie et al. 2006). The concept was developed in France but is currently applied in most European countries, from the Mediterranean[14] to Scandinavia. For each individual tree in such a plot, data are recorded on location, species, diameter at breast height and tree height. For Closer-to-Nature Forest Management further parameters such as crown base height, tree-related microhabitats, timber quality, dead wood, carbon equivalents may also be assessed. Marteloscopes can be applied for a variety of educational aims based on targeted participants often having varying expertise levels around topics including silviculture, wood production, or biodiversity (Kraus et al. 2018). Thus, they provide highly effective communication platforms where foresters, nature conservation managers, forest owners, students or interested societal groups meet and discuss aspects of economic and nature conservation values as well as the impacts of management decisions on other ecosystem services. The European Integrate Network has also embraced marteloscopes as a communication and training tool for mutual learning at the interface of research, policy and practice (Schuck et al. 2020). To date more than 160 sites in 22 countries are part of this network.

13 https://www.prosilva.org/activities/afi/
14 https://www.lifegoprofor.eu/it/download/category/20-martelloscopi.html

We are living in a time of accelerated changes and unprecedented global challenges: energy security, natural resource scarcity, biodiversity loss, fossil-resource dependence and climate change. Yet the challenges also demand new solutions and offer new opportunities. The cross-cutting nature of forests and the forest-based sector provides a strong basis to address these interconnected societal challenges, while supporting the development of a European circular bioeconomy.

The European Forest Institute is an unbiased, science-based international organisation that provides the best forest science knowledge and information for better informed policy making. EFI provides support for decision-takers, policy makers and institutions, bringing together cross-boundary scientific knowledge and expertise to strengthen science-policy dialogue.